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Cold Gas and Dust at High Redshift

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A Joint Discussion on the Topic of Cold Gas and Dust at High Redshift
D.J. Witmer 1

Dust Absorption and Emission in Galaxies at High and Low Redshifts
S. Michael Fall 2

Dust in Evolving Galaxies
Paola Andreani 6

Atomic Hydrogen at High Redshift
F.H. Briggs 10

Submillimeter Surveys at High Redshift
Amy J. Barger 14

The Dawn of Galaxies: Deep MAMBO Imaging Surveys
F. Bertoldi et al. 18

Gas and Dust in Ultraluminous Infrared Galaxies
D. Downes 22

Molecular QSO Absorption Line Systems
C. L. Carilli & K. M. Menten 26

ISOCA Deep Surveys and the Cosmic Infrared Background
David Elbaz 30

Hidden Star Formation: The Ultraviolet Perspective
G.R. Meurer et al. 34

Prospects for Future far-infrared/submillimeter Studies
Andrew W. Blain 38
A Joint Discussion on the Topic of Cold Gas and Dust at High Redshift

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The number of spectroscopically confirmed galaxies at high redshift galaxies is increasing rapidly, with many being found efficiently by deep optical imaging and color selection. In parallel, a confluence of technical developments is bringing rapid progress to the domain of observations of cold gas and dust at high redshift. Large telescopes operating at high, dry sites, with a new generation of sensitive detectors, together with recent satellite missions, are opening up new areas of study through observations of dust continuum emission and associated atomic and molecular emission and absorption lines. These data bear directly on fundamental questions of cosmic evolution by probing the ordinary cool material that forms stars and fuels active galactic nuclei. Analysis of data from the COBE satellite confirms the presence of a diffuse far-infrared background from a widespread population of distant dusty objects. The global energetics of the optical and far-infrared backgrounds suggest that perhaps half of distant activity may be enshrouded by dust. Understanding the nature and redshifts of the sources responsible for these emissions is profoundly important. The intent of Joint Discussion 9, between Division X (Radio Astronomy) and Division XIII (Galaxies and the Universe), was to provide a forum to present observations from this newly accessible realm and to consider the astrophysical implications.

Joint Discussion 9 at the XXXIVth IAU General Assembly, in Manchester, England, took place on August 14, 2000. A series of eleven speakers reviewed the following key scientific themes: Origin of Dust and Evolution of Galaxies (Fall, Andreani), Atomic Gas at High Redshift (Briggs), Far-Infrared, Submillimeter and Millimeter Surveys of Dust Content at High Redshift (Elbaz, Barger, Bertoldi), Molecular Gas in Emission and Absorption at High Redshift (Carilli), The Optical Perspective on Hidden Star Formation (Meurer), Gas and Dust in Ultraluminous Galaxies (Downes), and Future Prospects (Kawabe, Blain). The day closed with a lively open discussion from all participants on controversial issues. We hope these discussions have helped to set the stage for advances expected from the many international instruments now under construction, including the Submillimeter Array, the Large Millimeter Telescope, the Atacama Large Millimeter Array, and the SIRTF, FIRST, and PLANCK missions.

Acknowledgments. I thank James Moran for the initial suggestion to organize this session, the JD9 scientific organizing committee for selecting excellent speakers, the many participants for their timely contributions, and the IAU for support.
Dust Absorption and Emission in Galaxies at High and Low Redshifts

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Abstract. This article reviews three related topics: the extragalactic background light and its sources, evolution models for the dust absorption and emission in galaxies, and empirical constraints on these transfer processes in nearby starburst galaxies. It is intended that the material presented here will serve as an introduction to this Joint Discussion.

1. Extragalactic Background Light

A good place to begin our discussion of the effects of dust on the radiation from galaxies is with the extragalactic background light (EBL). We denote the intensity of this isotropic radiation per unit frequency $\nu$ by $J_\nu$ and the integral of this over all $\nu$, the bolometric intensity, by $J_{\text{bol}}$. By definition, $J_\nu$ excludes foreground radiation from the Milky Way and other nearby galaxies and the cosmic microwave background radiation from the Big Bang, but it includes the radiation from everything in between. A few years ago, we had only rough estimates and upper or lower limits on $J_\nu$ at most wavelengths, but this situation has improved dramatically, thanks largely to HST and COBE. We now know $J_\nu$ to an accuracy of a factor of two or better over four decades in wavelength, from about 0.2 to 2000 $\mu$m. This is shown in Figure 1 below.

Two interesting results follow directly from Figure 1. First, emission by dust is important. There is at least as much energy in the long-wavelength hump of the EBL spectrum ($\lambda \gtrsim 10$ $\mu$m) as in the short-wavelength hump ($\lambda \lesssim 10$ $\mu$m). Second, integrations under the smooth curves in Figure 1 give

$$J_{\text{bol}} \approx 50 \text{ nWm}^{-2}\text{sr}^{-1}. \quad (1)$$

This is a summary record of the bolometric emissivity $E_{\text{bol}}$ (power radiated per unit comoving volume) integrated over the age of Universe $t_0$:

$$J_{\text{bol}} = \frac{c}{4\pi} \int_0^{t_0} \frac{E_{\text{bol}}}{1+z} \, dt. \quad (2)$$

Equations (1) and (2) provide valuable constraints on possible sources of the EBL, independent of the complex radiative transfer within galaxies.

The most promising sources of the EBL are stars (nuclear energy) and AGN (accretion onto black holes, gravitational energy). Equation (2) enables us to express these contributions to the EBL in terms of the present comoving densities of stars and black holes (normalized by the critical density). Recent
estimates give $\Omega_s \approx 4 \times 10^{-3}$ and $\Omega_{BH} \approx 2 \times 10^{-5}$ for $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$.

For stars, we obtain from population synthesis models

$$J_s \approx 50 f(\Omega_s/4 \times 10^{-3}) \text{ nW m}^{-2}\text{sr}^{-1},$$

where $f \approx 1$ depends on the history of star formation and the initial mass function. For AGN, we obtain

$$J_{AGN} \approx 6(\epsilon/0.05)[3/(1 + z_{acc})](\Omega_{BH}/2 \times 10^{-5}) \text{ nW m}^{-2}\text{sr}^{-1},$$

where $\epsilon$ is the efficiency of energy conversion (gravitational to radiative) and $z_{acc}$ is the effective redshift of accretion. According to these estimates, which have substantial uncertainties, stars alone could produce the entire EBL, while AGN may make a significant but smaller contribution. Similar conclusions have been reached by Fabian & Iwasawa (1999) and Madau & Pozzetti (2000).

2. Evolution Models

Several methods have been developed to interpret or predict the appearance of galaxies at different redshifts and their contribution to the cosmic emissivity and EBL. In many cases, the absorption and reradiation of starlight by dust is governed by an effective optical depth $\tau_{\text{dust}}$ that is related to the metallicity, column density, and mass of the interstellar medium, $Z_{\text{ISM}}, N_{\text{ISM}}, M_{\text{ISM}}$, and
the size of a galaxy $R_{\text{gal}}$ by expressions of the form
\[
\tau_{\text{dust}} \propto Z_{\text{ISM}} N_{\text{ISM}} \propto Z_{\text{ISM}} (M_{\text{ISM}} / R_{\text{gal}}^2).
\]
(5)

The mass and metallicity of the ISM are then related to the prior history of star formation by the equations of galactic chemical evolution, with or without inflow or outflow terms. Most recent models can be classified into three types: "backward" evolution models, "forward" evolution models, and "global" evolution models.

In backward evolution models, the present-day population of galaxies is evolved into the past using plausible rules for the histories of star formation, gas consumption, and so forth in galaxies of different types (see Franceschini et al., 1994 and references therein). Interactions and merging of galaxies are usually ignored in this approach. In forward evolution models, initial distributions of dark matter and baryons are evolved into the future using plausible rules for the merging of halos, inflow and outflow of gas, and so forth (see Granato et al., 2000 and references therein). These effects are usually treated by semi-analytical techniques in the framework of the cold dark matter cosmogony. Since this approach includes many different processes, it requires a large number of assumptions and parameters.

Global evolution models are based on the combined or average properties of galaxies (see Pei, Fall, & Hauser 1999 and references therein). The quantities of interest here are the mean comoving densities of stars, ISM, metals, and dust ($\Omega_S$, $\Omega_{\text{ISM}}$, $\Omega_M$, and $\Omega_D$) and the mean comoving emissivities of stars and dust ($E_{\Omega_s}$ and $E_{\Omega_d}$). These quantities are governed by simple, conservation-type equations, analogous to the equations of galactic chemical evolution. The input to and output from the global evolution models include both emission and absorption-line observations, i.e., information about both the stellar and interstellar contents of galaxies. The advantages of this approach are that it is based directly on global quantities, requires relatively few assumptions and parameters, and relates the emission histories of galaxies to their absorption histories. A limitation of the global evolution models is that they do not describe the properties of individual galaxies and hence cannot be compared with luminosity functions and number counts. Moreover, the accuracy that is currently achievable is limited by small-number statistics in the existing samples of damped Ly$\alpha$ absorbers.

3. Nearby Starburst Galaxies

To determine the rate of stellar nucleosynthesis or black hole accretion in a galaxy, one must measure its bolometric luminosity. However, this is not currently practicable for most of the apparently faint galaxies at high redshifts. Most observations of high-redshift galaxies are restricted to rest-frame UV and optical wavelengths, which miss the light that is absorbed and reradiated by dust. Recent observations at 850 $\mu$m with SCUBA help, but much of the dust emission is almost certainly at shorter wavelengths. This situation has prompted several schemes to correct the observed UV and optical fluxes to bolometric fluxes. One of the most promising of these was discovered by Meurer et al. (1995) and refined by Meurer, Heckman, & Calzetti (1999).
Dust Absorption and Emission

The Meurer et al. relation is based on the observed properties of UV-selected, nearby starburst galaxies. These are of special interest because they may be low-redshift analogs of the high-redshift (z \approx 3-4) galaxies revealed by the Lyman-break technique (Steidel et al. 1996). In the nearby sample, Meurer et al. found a relatively tight correlation between the ratio of FIR and UV fluxes, $F_{\text{dust}}/F_{1600}$, and the UV spectral slope, $\beta$. The correlation may also hold for the Lyman-break galaxies, although the observational tests for this are not strong (Adelberger & Steidel 2000). The Meurer et al. relation is useful because, for galaxies that obey it, one can infer the FIR flux $F_{\text{dust}}$ and hence the bolometric flux from observations in the rest-frame UV ($F_{1600}$ and $\beta$). In this way, Meurer et al. (1999) and Adelberger & Steidel (2000) have estimated bolometric correction factors of about 5 between the UV-only and total star formation rates in Lyman-break galaxies at $z \approx 3-4$.

The existence of the Meurer et al. relation is closely linked to the existence of a “universal” effective absorption curve, although not quite the same as the one proposed by Calzetti, Kinney, & Storchi-Bergmann (1994). In this case, the parameter along the sequence is the effective optical depth at some fiducial wavelength and hence the overall dust content of the galaxies. Another curious fact about the UV-selected, nearby starburst galaxies is that the apparent absorption inferred from the H$\alpha$/H$\beta$ ratio is typically twice that inferred from the UV spectral slope $\beta$ (Calzetti et al. 1994). In an effort to understand these observations, Charlot & Fall (2000) have constructed some simple models in which stars are born in dusty clouds with finite lifetimes. As a result, young, UV-bright stars are more obscured than old, UV-faint stars. In particular, the Meurer et al. relation, and the other average spectral properties of the UV-selected, nearby starburst galaxies, can be reproduced if the effective absorption is proportional to $\lambda^{-0.7}$ and is three times higher for stars younger than $10^7$ yr than it is for older stars.

References

Dust in Evolving Galaxies

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Abstract. I will first review the observational evidence relating dust emission and the energy production in the far-IR/sub-mm range. This latter contains crucial information on the global baryons transformation and the related stellar activity in the Universe. Present knowledge on this topic relies mainly on the far-IR local surveys of IRAS and ISO missions and on sub-mm/mm surveys performed with SCUBA and MAMBO arrays. Further constraints are provided by the measurements of the Cosmic far-IR Background (CFIRB).
Our scanty knowledge of galaxy formation and evolution is mainly caused by the difficulties of unveiling stellar activity at redshifts larger than 1 and at present we may only have detected massive objects in a transient hyper-luminous phase. We still lack an unbiased census of the much more numerous population of lower luminosity dusty objects. It will soon be possible to disclose the entire history of evolving dusty objects, and therefore of the stellar activity, selecting unbiased samples out of far-IR imaging and photometry in deep far-IR surveys.

1. Dust Emission as Star-Formation Tracer

In the last twenty years, observational evidence has been accumulating that the most important episodes of star-formation in the local Universe and up to \( z = 1 \) happen in dusty and gaseous environments. But also at \( z > 1 \) there are indirect indications of an important role of dust: the existence of hyper-luminous high-z IR galaxies, the large amounts of processed material (dust and metals) in quasars and radio galaxies, the occurrence of dust extinction in optically selected galaxies at \( z = 2 \pm 4 \) (hence biased against dust obscuration), the presence of an integrated emission, in the form of a far-IR/sub-mm isotropic background corresponding to a very energetic high-z phase, and the population of energetic sub-mm/mm sources with very large star-formation rate (\( \sim 10^2 M_\odot \text{yr}^{-1} \)).

1.1. Constraints on the stellar activity history from the IR energy production

It is possible to trace back the stellar activity history by studying the evolution of the IR radiation production (Gispert, Lagache & Puget 2000). Current observations provide useful constraints on this history:
Dust in Evolving Galaxies

- At low redshifts $z < 1$ local IR surveys (IRAS and ISO) showed a population of high luminosity objects, with no or very faint optical counterpart, corresponding to merging or interacting systems for which the ratio between the IR to the optical luminosity, \( \frac{L_{\text{IR}}}{L_{\text{opt}}} \), increases as the bolometric luminosity increases. ISO deep surveys showed how the IR energy production strongly increases in the redshift range between 0 and 1, with deep galaxy counts significantly exceeding the non-evolving predictions.

- At redshifts between $z = 2$ and $z = 4$ measurements of the CFIRB constrain well the energy production and the number of sources giving origin to the CFIRB while present surveys are not sensitive enough.
  (a) The large value of the ratio, \( \frac{E(FIR)}{E(\text{opt})} = 1 - 2.6 \), between the background energy content in the far-IR (at \( \lambda \geq 6\mu m \)) and that in the optical (\( \lambda < 6\mu m \)) with respect to that measured in the local systems, \( \frac{E(FIR)}{E(\text{opt})} = 0.3 \), means that the galaxy population responsible for the stellar activity underwent a major change in its properties.
  (b) The energy content at $15 \mu m$ is nearly as large as in the optical. But the background at $15 \mu m$ is made up of a very small number of objects compared to the number of sources responsible for the optical background.
  (c) The spectrum of the CFIRB at long wavelengths is significantly flatter than that of individual IR galaxies. Therefore the submm part of the CFIRB cannot be due to the same population that gives rise to the background at $150 \mu m$ and contains unique information about the high-redshift population.

- Current submm/mm surveys address issues to the stellar activity at high-$z$ because of the shift of the thermal emission spectrum into their wavelength bands. SCUBA surveys detected high-luminosity objects with a large star-formation rate ($> 200M_{\odot} yr^{-1}$). The faint submm counts significantly exceed a no-evolution model requiring roughly $(1+z)^3$ luminosity evolution out to $z \sim 2$, but with poor constraints at higher redshifts.

In summary, star-formation activity, as detected in the far-IR, appears in total at least comparable to all that seen unobscured in the UV.

2. Lower Luminosity Dusty Objects

The outlined observational status suggests that the bulk of the CFIRB is very likely due to a small number of energetic sources (ISOCAM galaxies at $15 \mu m$, SCUBA galaxies at $850 \mu m$, ...) with a possible 20% contribution of AGN activity caused by dust enshrouded AGN + star-formation, which could have been higher in the past. These objects alone, however, fail to reproduce the optical/UV background, and are linked to massive dust distributions and/or large systems in advanced stages of chemical evolution and in an accelerated phase of evolution.

Their evolutionary pattern is quite different from that expected for disc-dominated galaxies, which form stars quiescently and continuously during a large fraction of Hubble time.


Where and what is this much more numerous population of lower luminosity dusty objects? As discussed below only future far-IR surveys will address this issue in a complete and unbiased way.

2.1. **Do Extremely Red Objects hide a dusty population?**

High-z dusty galaxies can be singled out among candidates selected according to their extreme red colours ($5 < R - K < 8$). The nature of these extreme red objects (EROs) is still controversial (see Cimatti et al. 2000 and references therein), being their large red colours due to either a passively evolving population of stars in old L* ellipticals at $z>1$ or to strongly extincted starbursts or AGNs whose UV-optical light is reddened by dust.

In principle it is possible to distinguish the two classes performing (1) near-IR Spectroscopy to detect either emission lines (Ha) of ongoing star-formation or sharp spectral breaks due to old stellar populations; (2) submm/mm observations to detect dust thermal emission and radio observations to detect that part of the synchrotron emission correlated with star-formation; (3) high spatial resolution optical and near-IR images to study the morphology, which is expected to be regular, compact and central peaked for old ellipticals and irregular, asymmetric and distorted for dusty starbursts.

Because of the intrinsic difference of their spectral energy distribution, candidate dusty objects can be selected, in the redshift range $1 < z < 2$, from their IR colours on the plane (I-K),(J-K) (Pozzetti & Maucci 2000).

Follow-up observations of the thermal emission is mandatory to confirm their nature (Cimatti et al., in progress), here we report some results on the dusty class.

- **HR10** is so far the only targeted ERO with a measured spectroscopic redshift (Graham & Dey 1996). Submm/mm photometry and spectroscopy undoubtedly proved that this object is highly obscured, has a large thermal far-infrared luminosity, high star-formation rate ($\sim 700$ M$_\odot$ yr$^{-1}$) and a large molecular gas mass M(H$_2$) (1.6 x 10$^{11}$ h$_{50}^{-2}$ M$_\odot$) (Cimatti et al. 1998; Dey et al. 1999; Andreani et al. 2000).

- **EROs have been found among submm-selected objects** (Smail et al. 1999; Gear et al. 2000) with plausible redshifts between 2 and 4, implying that they could represent 10% of the faint submm population.

- **Submm/mm search for dusty emission in other 30 EROs suggests that 30% of the entire ERO population is dusty, with the reddest objects being more likely the more dusty ones.**

3. **Future search**

Since it is becoming more and more evident that the assembly of galaxies is taking place between redshift $z = 1$ and $z = 3$, where a peak of activity is detected, to unveil the nature of the expected numerous dusty population at this epoch the goal of future surveys must be:
Dust in Evolving Galaxies

- measure the redshifted dust continuum and/or non-thermal emission from forming objects in as many colours as possible,

- produce high-spatial resolution maps to reduce the large uncertainty on source identification because of (1) large positional errorbars and (2) lack of optical/near-IR counterpart,

- estimate the nature of the ionizing continua (e.g. nonthermal AGN versus thermal starburst continuum) with low- and high-excitation atomic and ionic fine-structure lines.

- measure redshifts, star formation efficiency (star formation per unit gas mass) in high redshift galaxies, dynamic and mass of the gas via the far-IR/submm [CI], [CII], [NII], [OI], [OIII] fine structure lines and molecules, CO.

Surveys must be carefully planned and all the statistical biases and observational limitations must be studied. The reliability of the results must be checked through Monte Carlo simulations and a large number of mock surveys must be built to determine what happens when a selection of a sample is made. This provides information on the observational biases introduced by the observing procedures and allow to understand how the different parameters affect the source observation and the detection.

This approach was followed by us to plan surveys with the PACS and SPIRE Instruments aboard of the FIRST Satellite. The approach we used is as much empirical as possible and uses a statistical analysis. It is generally called Backward Evolution since it starts from the present epoch and tries to extrapolate the local (statistical) properties of galaxies to higher redshifts to predict how sources formed, behaved and evolved since their birth.

The statistical properties on the evolving underlying population of objects are inferred from the luminosity function and its evolution, the spatial distribution of source via the angular correlation function, the integral and differential source counts and the integrated background due to the integrated emission from the unresolved sources.

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References

Atomic Hydrogen at High Redshift

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Abstract. After the production of the ionizing background by the first generation of stars, neutral gas must be confined to sufficiently high density to be self-shielding and remain neutral. Neutral gas is an identifier of the presence of confining gravitational potentials and a tracer of the kinematics of the potential. Kinematical studies are being extended to neutral atomic gas at high redshift.

1. Introduction

This discussion emphasizes three principal areas: the nature of galaxies selected for neutral gas content, the role of HI as a tracer of galactic potentials, and the “highest redshift HI” that constitutes the IGM during between the Epoch of Recombination and the period of reionization that is driven by the first generation of luminous objects.

The global neutral gas content of the Universe as a function of time shown in Figure 1 provides a framework for the discussion. This diagram begins at the recombination epoch at $z \sim 1000$ and continues to the present. The “Dark Age” (Rees 1996, 1999), during which the cosmic background radiation propagates freely through an IGM of neutral baryons, is ended when the first stars or luminous compact AGN-like objects generate the ionizing background radiation that is responsible for ionizing the bulk of the Universe's baryons. There has been a remarkable convergence toward agreement of empirical evidence on the number of baryons through the measurement of light elements combined with Big Bang Nucleosynthesis models (Tytler et al. 2000) and through measurements of the CMB fluctuation spectrum (Hu et al. 2000). This fixes the cosmological density of neutral gas through the Dark Age. Just when and how the Dark Age ends is the subject of great current interest for both theorists and observers.

2. Nature of HI selected galaxies

Through the period of galaxy assembly and most vigorous star formation, we monitor the neutral gas content of the Universe through the damped Lyman–$\alpha$ DLA absorption line seen against the continuum of quasars. At very low redshift, we determine the HI content and general distribution of neutral gas through blind and targeted 21cm line observations of nearby galaxies. Figure 1 shows a marked drop in $\Omega_{\mathrm{HI}}$ between DLA points and the 21cm values, leading to the concern that the HI content of the nearby Universe might be severely underesti-
Atomic Hydrogen at High Redshift

![Graph showing the relationship between the logarithm of the neutral gas density and the age of the Universe.](image)

Figure 1. Cosmological density of neutral gas, $\Omega_{\text{gas}}$, as a function of the age of the Universe since the Recombination Epoch. The neutral gas content during the Dark Age is equal to the baryonic mass density. The timing of the Epoch of Reionization EOR is not yet well determined, falling somewhere in the redshift range 5 to 30. The filled square data points come from Damped Lyman–$\alpha$ quasar absorption-line statistics (Wolfe et al. 1998, Rao & Turnshek 2000), and the open circle at the present epoch results from surveys in the 21cm line. A light shaded area is drawn to represent the rise in the baryonic content of stellar populations after the EOR, until reaching the measured value at present (open square).

estimated or hampered by incompleteness. This is not the case – a series of “blind” HI surveys of significant volumes of sky (Zwaan et al. 1997, Spitzak & Schneider 1998, Kilborn et al. 1999, Rosenberg & Schneider 2000) now show that HI clouds reside either in the galaxies disks, where they exhibit galactic revolution, or they sit in the halos of galaxies, as tidal debris, streams, small clouds or dwarf galaxies. There are no known cases of “free floating” intergalactic clouds not associated with a star-bearing galaxy or galaxy group.

The astrophysics of neutral gas clouds and the absence of intergalactic specimens is probably quite simple: clouds must be confined to sufficiently high density that they can remain neutral in the face of an ionizing background radiation field. Clouds that are not confined become ionized and join the bulk of the Universe's baryons that constitute the intergalactic medium (Shull et al. 1999). The gravitational potentials provided by galaxy halos are natural confinement vessels for hydrogen, but once confined to adequate density to become self-shielding, the gas is also vulnerable to the instabilities that give rise to star formation. There appears to be an inevitable association of HI with stars in the nearby Universe (Zwaan 2000).

A net result of the 21cm line observations is that there has been a convergence on a value for the integral HI content of the local Universe, both from the blind HI surveys (Zwaan et al. 1997) and from 21cm line observations that target optically selected galaxies (Fall & Pei 1989, Rao & Briggs 1993).
At high redshift, HI-rich objects are selected through damped Lyman–α absorption (Wolfe et al. 1986). While much progress is being made in measuring the evolution of metal content in these neutral clouds (Pettini et al. 1997, 2000, Prochaska & Wolfe 2000), the identification of the galaxies that host the HI clouds has been extremely difficult (see for example Ellison et al. 2000), even at redshifts less than one (Steidel et al. 1994, Rao & Turnshek 1998), causing basic questions about the morphologies of the hosts to remain unanswered.

Somerville (2000) has recently reviewed the controversial hypotheses about the nature of DLA absorbers. Opinions range from large, well-formed disk-like systems (Prochaska & Wolfe 1997, 1998) to a collection of small objects in mid-merge (Hachnelt, Steinmetz & Rauch 1998). At both extremes, the authors comment that the DLAs are likely to be the “best probe of the progenitors of the normal present-day galaxies.”

The DLA systems are selected for their HI absorption cross section rather than optical brightness, and it is likely to require gas-sensitive observational techniques to determine their nature and relation to present day galaxies. A direct measurement of the HI content of these high redshift galaxies at z ~ 3 to 4 will be possible with a next-generation radio telescope such as the Square Kilometer Telescope SKA (van Haarlem 1999). Current telescopes, including Westerbork, VLA and the new GMRT in India, will be effective to redshifts Z ~ 0.3.

3. Prospects for kinematic studies in HI at high Z

High spectral resolution kinematic studies of the low-ionization metal lines formed in the DLA gas layers have been central to the controversy over the nature of the DLAs. As in the 21cm line synthesis mapping of galaxies that led to the measurement of dark matter content and distribution in spiral galaxies in the nearby universe, the large velocity spreads observed for the metal lines may be indicative of gas motions in massive potentials.

Since neutral gas must be confined to be self-shielding to the ionizing background, it is likely to be the optimal kinematical tracer. Tidal interactions that disperse gas or supernova ejections that shock it, will lead to ionization and disappearance from detectability to HI sensitive probes. Conventional 21cm line mapping observations could be extended to redshifts ~1 with SKA, but mapping the detailed kinematics of 21cm emission from z > 1 galaxies is likely to remain out of reach.

There are good prospects, however, for mapping HI in absorption against extended background radio sources with existing instrumentation. An example of how this might work is shown by the observation of 3C196 by Briggs, de Bruyn and Vermeulen (see Briggs 1999).

4. Epoch of reionization

The Dark Age between the epoch of recombination and the epoch of reionization is also the “great epoch of neutrality.” There has been a recent surge of theoretical interest in the first generation of stars and their effect on the neutral IGM. Little is yet known observationally, and there are only loose constraints on the
redshift range over which reionization occurs: Numerical simulations favor $Z_{\text{eom}}$ from 8 to 20. $Z_{\text{eom}}$ cannot be more recently that $z \sim 5.5$ since UV continuum can be detected against the highest redshift QSOs (Zheng et al. 2000); $Z_{\text{eom}}$ cannot be greater than 30 without causing observable suppression of the first peak in the power spectrum of anisotropies in the CMB (de Bernardis et al. 2000). Two recent papers (Shaver et al. 1999, Tozzi et al. 2000) address the possibilities for direct radio observation of the neutral gas through this period when the first stars form and the seed of galactic structures emerge. This Epoch of Reionization is one of the next frontiers of observational cosmology.

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Submillimeter Surveys at High Redshift

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Abstract. Deep submillimeter (submm) surveys offer an unobscured view of dust-enshrouded star formation or AGN activity at high redshifts. SCUBA observations above 2 mJy have resolved 20 – 30% of the far-infrared (FIR) background into discrete sources and have revealed the existence of a distant population of galaxies with properties similar to those of local ultraluminous infrared galaxies. A large fraction of the submm sources have extremely faint optical/near-infrared (NIR) counterparts and hence are inaccessible to optical spectroscopy. Millimetric redshift estimation places the submm population at z = 1 to 3. While the cumulative surface density of the submm sources is low, they are so luminous that if powered mainly by star formation, they dominate the high redshift star formation history. Recent combined SCUBA submm and Chandra hard X-ray studies suggest that the majority of the submm sources are star formers with a only small admixture of obscured AGN.

1. Introduction

The cumulative emission from all objects lying beyond the Galaxy, the extragalactic background light (EBL), provides important constraints on the integrated star formation history of the Universe. The recent measurements of the EBL at FIR and submm wavelengths using data from the FIRAS and DIRBE experiments on the COBE satellite (e.g., Puget et al. 1996; Fixsen et al. 1998) indicate that the total emission from star formation and AGN activity that is absorbed by dust and reradiated into the FIR/submm is comparable to the unobscured emission seen in the optical. This suggests that obscured star formation may be responsible for a large fraction of the stars and metals seen in the local Universe.

Reradiation of light by dust into the FIR produces a thermal emission peak at \( \lambda \sim 100 \mu m \) that is redshifted into the submm for galaxies at \( z > 1 \). Submm observations are unique in having a strong negative K-correction that compensates for cosmological dimming beyond \( z \approx 1 \), thereby making dusty galaxies almost as easy to detect at \( z \approx 10 \) as at \( z \approx 1 \). The Submillimeter Common User Bolometer Array (SCUBA; Holland et al. 1998) on the James Clerk Maxwell 15 m telescope on Mauna Kea provides the sensitivity and area coverage to image directly the sources producing the submm EBL. SCUBA surveys have uncovered numerous sources with properties similar to those expected for the distant counterparts to the most luminous, merging systems observed locally, the ultra-
luminous infrared galaxies (ULIGs; Sanders & Mirabel 1996). If the majority of the submm emission in these systems comes from dust-obscured star formation, then their inferred star formation rates are spectacular, on the order of several hundred solar masses per year.

2. Submillimeter Counterparts and the Radio Advantage

Identifying the optical/NIR counterparts to the submm sources is difficult due to the uncertainty in the SCUBA positions and the intrinsic faintness of the sources. Barger et al. (1999) presented a spectroscopic survey of possible optical counterparts to a flux-limited sample of galaxies selected from the 850 μm survey of massive lensing clusters by Smail, Ivison, & Blain (1997). Candidate optical counterparts in the SCUBA error-boxes were identified using moderately deep ground-based and HST exposures \((I \sim 23.5 \text{ and } I \sim 26\), respectively). One-quarter of the sources could be reliably identified, and those had redshifts in the range \(z \sim 1\) to 3. A lower limit of 20% of the full sample showed signs of AGN activity. However, for the majority of the submm sources there were either no optical counterparts or the optical associations were not secure.

High resolution radio continuum maps with subarcsecond positional accuracy and resolution offer new opportunities for locating submm sources and determining their physical properties. About 20% of the sources in an ultradeep radio map of the Hubble Deep Field region at 1.4 GHz (Richards 2000) are undetected in ground-based optical imaging to \(I \sim 25\), and this population has been shown to contain the bright submm source population (Barger, Cowie, & Richards 2000). An important corollary is that a large fraction of the sources in submm surveys have extremely faint optical counterparts and hence are inaccessible to optical spectroscopy. Redshift estimates made from the ratios of the submm fluxes to the radio fluxes (Carilli & Yun 2000) place the bright submm sources at \(z \sim 1\) to 3 where they form the high redshift tail of the faint radio population.

3. Towards a Star Formation History

Observations of high redshift sources are often interpreted using the comoving volume-averaged history of star formation diagrams introduced by Madau et al. (1996). Measurements are typically based on the rest-frame ultraviolet (UV) luminosity function, whose origin is assumed to be young stellar populations. However, dust plays an important role in the high redshift Universe. Recent estimates suggest that dust obscuration of high redshift optical sources result in upward corrections by factors of 3 to 5 (e.g., Pettini et al. 1998; Meurer, Heckman, & Calzetti 1999) in the star formation rate density, but these corrections are rather uncertain. Moreover, many objects may be so extinguished that ultimately only submm studies can reliably determine how much light is hidden, and, in particular, whether the most rapid and obscured massive star formers are completely missed in optical surveys.

Any attempt at tracing the dust-obscured star formation history of the Universe also requires knowledge of the extent of the contribution that AGN make to powering the submm sources. X-ray surveys provide the most direct and un-
biased probe of massive black hole accretion activity throughout the Universe, particularly in the hard X-ray band above 2 keV where most of the energy density of the extragalactic X-ray background (XRB) resides. Early observations with the Chandra satellite have resolved more than 70% of the 2–8 keV XRB into point sources ( Mushotzky et al. 2000; Garmire et al., in preparation). Unexpectedly, approximately half of the hard XRB emission is from relatively local luminous early-type galaxies in the redshift range z = 0 to 1 (Barger et al. 2001). The X-rays arise from the cores of these galaxies, presumably as a result of AGN activity, but most of the galaxies show no clear AGN signatures in their optical spectra. Most of the remainder of the XRB emission is produced by much fainter optical sources (I > 23.5) whose colors are consistent with evolved early galaxies at z > 1.5. If the hard X-ray sources are highly absorbed, then the rest-frame soft X-ray through NIR radiation will be reprocessed by dust and gas and the energy will appear in the FIR.

4. Hard X-ray Properties of a Submillimeter Selected Sample

The results of recent searches for Chandra hard X-ray counterparts to submm sources have been mixed. In a study of two clusters by Fabian et al. (2000), only a marginal source was seen in both the X-ray (2.8σ) and submm (2σ) datasets. Likewise, none of the submm sources in the ultradep Hubble Deep Field SCUBA map of Hughes et al. (1998) was detected in the 2–8 keV band by Hornschemeier et al. (2000). In contrast, two of the submm sources in the A370 lensed field of Smail, Ivison, & Blain (1997) were detected in the 2–10 keV band by Bautz et al. (2000). These two sources had previously been identified spectroscopically as AGN (Ivison et al. 1998; Barger et al. 1999). The above mixed results probably reflect the fact that the 850 μm flux limits obtainable with SCUBA are quite close to the expected fluxes from obscured AGN.

Barger et al. (2001) compared wide-area and ultradep submm maps (Barger, Cowie, & Sanders 1999; Barger et al. 1998) with the SSA13 deep Chandra X-ray map of Mushotzky et al. (2000). The 2–10 keV fluxes for each of the twelve submm sources detected in the high quality X-ray region were measured in 10′ diameter apertures. Only one submm source was found to be a strong hard X-ray emitter. The submm source with the second strongest hard X-ray flux is not a significant hard X-ray source but is a known soft X-ray emitter (Mushotzky et al. 2000).

The ratio of the total hard X-ray flux in the sample to the total submm flux is 1.4 ± 0.5 × 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ mJy}^{-1}. This ratio can be used to estimate the fraction of the hard XRB that arises from submm sources in this flux range. The EBL of the 2–10 mJy source population is 9.3 × 10^{3} \text{ mJy deg}^{-2} (Barger, Cowie, & Sanders 1999), which would contribute 1.3 × 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2} in the 2–10 keV band or 6% of the hard XRB, if the Vecchi et al. (1999) value of 2.3 × 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2} is adopted.

However, nearly all of the X-ray signal from the submm sample is coming from one source. If this single source is removed, the total hard X-ray to total submm flux ratio drops to 0.6 ± 0.5 × 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ mJy}^{-1}. If the submm sources are assumed to lie at z = 2 (consistent with the z = 1–3 spectroscopic and millimetric redshift range for submm sources), then the 1σ lower limit on
the ratio of the FIR luminosity to the hard X-ray luminosity is approximately 1100. This lower limit is above the values for obscured AGN (~ 10 — 100) and approaching that of Arp 220 (3.4 x 10^4). It therefore appears that most of the submm sources, at least above 2 mJy, are star formers with a small admixture of obscured AGN.

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The Dawn of Galaxies: Deep MAMBO Imaging Surveys

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Abstract. We discuss results from sensitive, wide-field imaging of the millimeter extragalactic background using the Max-Planck Millimeter Bolometer array (MAMBO) at the IRAM 30 m telescope.

The detection of a far-infrared and sub-millimeter wavelength background by COBE, and the first sensitive, high-resolution SCUBA images of the sub-mm background have caused significant revisions of our picture of the star-formation history of the universe. SCUBA at 850 µm discovered a population of what appear to be star forming galaxies at high redshifts, most of which are invisible at optical and near-IR wavelengths (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1999; Eales et al. 1999; Bertoldi et al. 2000). The infrared luminosities of these objects are comparable to the bolometric luminosities of QSOs, but their optical faintness shows that, unlike for QSOs, nearly all of the bolometric luminosity arises from thermal emission of dust grains. The emitting dust is probably heated in massive, optically obscured star forming regions, with star formation rates \( \sim 10^2 M_\odot \text{yr}^{-1} \). The objects discovered with SCUBA and MAMBO can account for the integrated (sub)mm background, and thereby about 25% of the total infrared background radiation. The relation between metal production and the extragalactic background (Eales et al. 1999) would then imply that at least a quarter of all stars were formed during the extreme starbursts we now see as thermal background sources.

The total number of (sub)mm background sources discovered with SCUBA at 850 µm (350 GHz), and with the 37-channel MAMBO array at 1.2 mm (250 GHz) now exceeds 100, and great efforts have been made trying to identify the class of known objects to which these (sub)mm sources belong. However, most of them defy a clear optical identification, and thereby an accurate redshift determination. The positional accuracies of the SCUBA and MAMBO sources are of order 5′, which for each source allows for a number of faint optical and near-IR sources as possible counterparts, objects which are usually too faint for spectroscopic studies. To date, only two MAMBO sources have clear near-IR identifications, and three SCUBA sources have clear optical or near-IR identifications with a spectroscopic redshift (Lilly et al. 1999; Ivison et al. 2000).

More promising are recent attempts to identify the (sub)mm background sources with radio sources in deep VLA images. We found that the majority of several dozen brightest and highest-S/N MAMBO sources in our 100 arcmin\(^2\) map of the Abell 2125 region have 20 cm radio counterparts within 5′ of the
MAMBO source position. Since in our 7.5\mu Jy rms noise 20 cm VLA map on average we find only one $> 5\sigma$ source per arcmin$^2$, chance alignments of radio and MAMBO sources are rare, and nearly all of the MAMBO-radio associations should be real. The radio identification of a MAMBO source determines its position within an arcsecond, and thereby allows a unique identification of any optical or near-IR counterpart, or as in most cases, the lack of one.

A radio identification also allows an approximate redshift determination. Relying on the tight correlation between the radio and the far-IR flux densities of star forming galaxies, Carilli & Yun (1999) showed that the radio-to-(sub)mm flux ratio decreases with increasing redshift to such an extent that the observed value of this flux ratio can be used to estimate redshifts up to $z \approx 4$. Although contributions to the radio flux from an AGN, or systematically higher dust temperatures compared to local starburst galaxies would lead to an underestimate of the redshifts (Blain 1999), the radio-to-(sub)mm flux ratios of several dozen SCUBA and MAMBO sources provide a unique first look at their redshift distribution, placing most of them at $z \approx 1$ to 4 (Fig. 2). Including SCUBA/MAMBO sources for which upper limits to their radio fluxes are
known, the redshift distribution shifts to slightly higher values, but it appears unlikely that there exists a dominant population of SCUBA/MAMBO sources at very high (z > 4) redshifts.

![Figure 2. Redshift distribution for 250 GHz (1.2 mm) and 350 GHz (850 μm) selected sources, based on the cm-to-mm flux density ratio for sources with radio detections at 1.4 GHz, including redshift lower limits based on radio upper limits.]

Figure 3 shows the preliminary cumulative source counts based on two of our three MAMBO deep fields, along with source counts determined from various SCUBA surveys. We relate the 250 GHz flux densities to 350 GHz flux densities using a scaling factor of 2.25, applicable to a typical starburst galaxy at z ≈ 2.5. We have included faint source counts in the regions within a 1’ radius of the cluster center assuming a mean gravitational magnification factor of 2.5. The MAMBO and SCUBA counts agree well at intermediate flux densities, and they show a steepening of the distribution at $S_{350} \approx 10$ mJy.

![Figure 3. Preliminary cumulative source counts from two MAMBO fields as large solid squares, plus counts from various SCUBA surveys. The dashed curve is a power law of index −1.6. All of the data can be reasonably fit by an integrated Schechter-type luminosity function, with parameters as given on the plot.]

What is the possible cause of a high brightness turnover of the (sub)mm background source counts? If these objects are indeed starbursts, then the implied star formation rates would be > 2000 $M_\odot$ yr$^{-1}$. Such extreme rates could only be sustained for some minimum (dynamical, free-fall, dissi-
pation) timescale by the most massive galaxies. A turnover in the brightness
distribution could thus indicate a turnover in the mass function of galaxies, or
alternatively, it may be the signature of an upper limit to the luminosity of a
starburst, an equivalent to the Eddington limit, determined by the energy output
of the burst and the ability of the gas to dissipate energy rapidly enough to
permit further mass infall or cloud collapse.

**What is the nature of the (sub)mm background sources?** It appears
unlikely that a large fraction of them are dust-enshrouded QSOs, since Chandra
observations failed to detect most of the targeted SCUBA sources (e.g. Fabian et al.
2000). However, two of the three SCUBA sources for which optical emission
lines were seen show signatures of an active nucleus. The brightest source found
in the MAMBO blind survey is an intermediate-redshift QSO, showing non-
thermal emission at mm wavelengths. In a SCUBA mapping survey Knudsen
et al. (2000) also find their brightest object to be a $z = 2.8$ QSO. These two
objects could be coincidental, but they do hint at a possible overlap of the
(sub)mm background and the QSO populations.

Most likely, much of the energy emitted by the (sub)mm background sources
arises from starbursts. Because then they produce a significant fraction of all
stars in the Universe, and because they are more luminous than any starburst
galaxy in the local universe, it is suggestive to think that they are elliptical
galaxies seen at the time when they formed most of their stars. It would be of
great interest to establish their exact redshift distribution. If they had formed
over a wide range of redshifts, they probably formed through the hierarchical
merging of smaller objects. If they formed in a narrow time interval at high
redshift however, it would suggest that they formed through the collapse of
single, massive primordial density enhancements. Our current estimate of their
redshift distribution is consistent with the latter picture, the monolithic collapse
of $10^{12} M_\odot$ structures, but this remains to be verified.

*The MAMBO surveys are a collaborative effort also involving R. Zylka, L. Re-ichertz, A. Bertarini, D. Lutz, H. Dannerbauer, L. Tacconi, and R. Genzel.*

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Gas and Dust in Ultraluminous Infrared Galaxies: Implications for Sources at High Redshift

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Abstract. High-z mm and submm dust sources are thought to be similar to ultraluminous infrared galaxies, where merger interactions have driven most of the gas and dust into circumnuclear molecular disks or rings with typical radii of 500 pc. Within these disks, CO and radio data indicate a new class of extreme starbursts, with characteristic sizes of 100 pc, gas masses of \(10^8 M_\odot\) and IR luminosities of \(\sim 3 \times 10^{11} L_\odot\) from OB stars. Some of these regions, however, harbor powerful AGNs, even though the optical IR diagnostics may classify them as starbursts. Trentham (2000) argues that averaged over time, most of the high-z dust sources must be powered by AGNs.

The high-redshift mm and submm dust sources have IR luminosities and SEDs similar to the local-universe ultraluminous infrared galaxies (ULIGs or ULIRGs; for a recent overview, see the proceedings of the 1998 Ringberg ULIG conference, edited by Lutz & Tacconi 1999). I review here some new ULIG results that have appeared since that conference, and the implications for interpreting the mm and submm detections at high redshift.

Major new data papers have appeared recently. Soifer et al. (2000) present 8 to 25\(\mu m\) images of 7 ULIGS from the Keck Telescopes with 0"3 to 0"6 resolution. The 25\(\mu m\) maps give the closest approximation to what the sources would look like at 100 \(\mu m\) if we could get 0"5 resolution at 100\(\mu m\). For example, in Arp 220 (Soifer et al. 1999) one interpretation of the 25\(\mu m\) map is that \(\sim 75\%\) of the total luminosity of the galaxy comes from the western peak.

Scoville et al. (2000) give HST NICMOS-camera images of 24 luminous IR galaxies, including 15 ULIGs, with resolution < 0"2. These are the highest-resolution ULIG images available in the near-IR. The data are given as separate maps at 1.1, 1.6, and 2.2\(\mu m\), as “true color” combined images of the three bands, and as ratio (color) maps, that show the regions of strongest extinction in the near-IR. There are some surprises, like the remarkable mini-spiral in the nucleus of VII Zw 31, which on ground-based images resembles a large elliptical galaxy.

Surace & Sanders (2000) present near-UV (3410 Å) images of 20 ULIGS. These images are important because they give an idea what ULIGs at \(z = 1\) would look like at 6800 Å, or what ULIGs at \(z = 2\) to 4 ought to look like in deep field images in the HST NICMOS bands.

Extreme starbursts: There is new evidence for extreme starbursts as substructure within the main ULIG dust and gas concentration. These are compact, 80 to 100-pc regions with strong, but extended, non-thermal radio continuum and compact radio supernovae, such as those found in the east and
west “nuclei” of Arp 220 (Smith et al. 1998). Another example is the group of radio supernovae in Mrk 273, seen at 1.4 GHz with the VLBA (Carilli & Taylor 2000) — all within a bright compact CO source suggestive of an extreme starburst region (Downes & Solomon 1998). The innermost parts of the rotating CO disk, are shown in MERLIN maps of H$\alpha$ absorption and OH megamasers (Cole et al. 1999; Richards et al. 2000; Yates et al. 2000).

**Transition objects:** There are new results on IR “warm” ULIGs, in which the black hole accretion luminosity, re-radiated by a dust torus in the NIR, is a large part of the power output. Some of these objects are classed both as ULIGs and as quasars. The prototype is Mrk 231, for which Keck observations (Soifer et al. 2000) yield a 12.5 $\mu$m size upper limit of $< 0.1$ (3$\sigma$, 100 pc), and a 60 $\mu$m size much larger than the 12.5 $\mu$m size. Soifer et al. note that the increase in size of the IR source with wavelength is consistent with an AGN of luminosity $3 \times 10^{12} \text{L}_\odot$, heating the surrounding dust and producing a radial temperature gradient.

Against this interpretation however, are a) the low power of the central AGN in hard X rays ($8 \times 10^8 \text{L}_\odot$, or $\leq 1\%$ of the bolometric luminosity; Nakagawa et al. 1999); b) the properties of the 350- pc radio continuum disk (short electron lifetimes, flat spectrum, consistency with the radio-FIR relation for starbursts; Ulvestad, Wrobel, & Carilli 1999); c) the free-free absorption of the disk at low frequencies, the 4 candidate radio supernovae in the disk (Taylor et al. 1999); d) the sum of X-ray, UV, visible, and NIR luminosities, all corrected for extinction, that yields $\leq 30\%$ of the bolometric luminosity (Downes & Solomon 1998).

New HST images of the IR “warm” ULIGs Mrk 231, Mrk 1014, and IRAS 07598+6508 (Canalizo & Stockton 2000) show the central quasars are surrounded by near-nuclear starbursts, for which photometry compared with starburst templates yield relatively young ages. In Mrk 231, Canalizo & Stockton derive an age of $\leq 40$ Myr for the starburst 3 kpc south of the nucleus. The starburst regions in the central 1 kpc around the quasar are very similar in both size and brightness, any may also be as young as the region at $r = 3$ kpc. The near-in starbursts are within the molecular disk mapped in CO (Bryant & Scoville 1996; Downes & Solomon 1998).

**NGC 6240:** While Arp 220 is often called the ULIG prototype, the luminous ($7 \times 10^7 \text{L}_\odot$) merging galaxy NGC 6240 is even more emblematic of the starburst-AGN debate. This merger shows dramatic tidal tails over a region $> 100$ kpc. Although the mid-IR lines observed by ISO would class this object as starburst-powered (Genzel et al. 1998; Rigopoulou et al. 1999), it contains a powerful AGN, as shown by its high luminosity in hard X rays ($\sim 10^{11} \text{L}_\odot$) and its 6.4 keV iron K-shell lines (e.g., Komossa & Schulz 1999; Nakagawa et al. 1999; Vignati et al. 1999; Ikebe et al. 2000). The HST NICMOS color map (Scoville et al. 2000) indicates maximum extinction between the two IR nuclei of NGC 6240. Tecza et al. (2000) mapped the 2 $\mu$m CO band head emission across the two K-band peaks separated by 1.6 to derive the rotation velocity and the velocity dispersion of the stars in the two nuclei. Both of these velocity measures correspond to large masses, much greater than that implied by the K-band light, which is dominated by red supergiants. These large masses imply that the K-band peaks are the massive, pre-merger nuclei, with the velocities indicating dynamical masses of (2 to 8) $\times 10^9 \text{M}_\odot$, mostly in old stars, within the central 500 pc of each nucleus. From their models of the K-band luminosity, Tecza et al.
derive a mass of $(0.4 \text{ to } 2) \times 10^8 \ M_\odot \text{, of new stars, formed in nuclear starbursts that last} 5 \text{ Myr, about 15 \ to \ 25 \ Myr ago. The gas, however, as traced in the mm lines of CO, is between the two K-band peaks, as if it has been driven by the two nuclei into the gravitational potential minimum between them (Tacconi et al. 1999; Bryant & Scoville 1999 AJ, 117, 2632). The interesting question is: where is the X-ray emitting supermassive black hole? — in the former nuclear bulges, or in the self-gravitating gas cloud in the middle? And does it power most of the far-IR luminosity of NGC 6240?}

**Trentham's Argument:** An interesting argument has been formulated by Trentham (2000). From their bolometric luminosity and spectral energy distribution, the submm dust sources detected with SCUBA appear to be the high-z analogs of the local-universe ULIGs. The only realistic end product of the ULIGs are cores of giant elliptical (gE) galaxies, and their supermassive black holes. The current ULIG number density is $1.1 \times 10^{-7} \text{ Mpc}^{-3}$, but that of giant elliptical galaxies is $1.6 \times 10^{-4}$, most of which have cores and supermassive black holes, which means that their progenitors, the high-z ULIGs, were 1500 times as numerous at earlier epochs ($z > 2$), consistent with the universe being smaller and mergers more frequent. The number density of high-z SCUBA sources is $10^{-4} \text{ Mpc}^{-3}$, so the story seems to fit. This explains the local number density of gE cores and supermassive black holes ($10^{-4} \text{ Mpc}^{-3}$) — they were the SCUBA sources at earlier epochs. This picture not only explains the local number density of gE cores, but also their size (radius several hundred pc), stellar density ($\sim 100 \ M_\odot \text{ pc}^{-3}$), and the fact that they are often kinematically decoupled from the rest of the giant elliptical. Furthermore, $M_{BH} \propto \sigma^4$, where $M_{BH}$ is the mass of the supermassive black hole, and $\sigma$ is the velocity dispersion of the central spheroid, implying that the mass of the black hole is one-third the mass of the gE core.

Trentham's argument is that if the high-z SCUBA sources have the same gas and dust distributions as local ULIGs, then, averaged over time, they must be powered by AGNs. The reason is that the ratio of accretion to nucleosynthesis luminosities per unit mass is $1760 \eta$, where $\eta$ is the efficiency of accretion luminosity, often taken to be 0.1. Since one-third of the core mass accretes onto the black hole, the net result is that, averaged over time, the accretion luminosity should be larger than the star formation luminosity by the factor $560 \eta$. Trentham supports his conclusion that the SCUBA sources must be powered by AGNs by noting that they give a bolometric background radiation of $7 \text{ nW m}^{-2} \text{ sr}^{-1}$, or 10% of the total bolometric luminosity of the universe, and about that expected from the production of supermassive black holes in gE cores, and also about that expected if the hard X-ray background comes from absorbed quasars that re-radiate at far-IR and submm wavelengths (Fabian & Iwasawa 1999; Almaini et al. 1999). This is in strong contrast to what the SCUBA sources could give by star formation, if the SCUBA sources have the same concentrated gas distribution as the local ULIGs. Since then their only realistic end products would be the gE cores, the SCUBA sources would form < 1% by mass of the stars in the universe. Hence their large power output would have to come from AGNs, not stars. Hence the SCUBA sources would not be the same as the local-universe ULIGs, for which only 1/3 appear to be powered by AGNs.
So far, however, the SCUBA observations of the CHANDRA deep X-ray field show that the high-z dust sources are generally not the same objects as the AGN X-ray sources (Barger et al. 2000), which may mean that they are not powered by AGNs, in contradiction to Trexham’s argument. Are the AGNs heavily obscured, as in NGC 6240?

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Molecular QSO Absorption Line Systems

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Abstract.

We review observations of molecular absorption line systems at high redshift toward red quasars and gravitational lenses.

The steeply falling power law column density distribution function of QSO absorption line systems implies that for every 1000 Ly α forest lines from absorbers with hydrogen column density, \( N_H < 10^{15} \text{ cm}^{-2} \) there will be only one system with \( N_H \geq 10^{22} \text{ cm}^{-2} \) (Hu et al. 1995). Although rare, these extreme high column density systems provide the most direct and detailed probes of the dense, pre-star-forming interstellar medium (ISM) in galaxies at substantial look-back times. Unfortunately, such high column densities also lead to substantial optical dust extinction, e.g., for a normal dust-to-gas ratio, \( A_V > 6 \) for \( N_H > 10^{22} \text{ cm}^{-2} \); hence finding such absorbers using optical spectroscopy is problematic. One method used for finding these systems is to search for molecular and HI 21 cm absorption toward flat spectrum radio sources with red (or absent) optical counterparts. Four high redshift molecular absorption line systems have been discovered this way, in two of which the absorption occurs in a gravitational lens (0218+357 at \( z = 0.685 \) and 1830–211 at \( z = 0.886 \); Wiklind & Combes 1995, 1996a). In the other two systems (1413+135 at \( z = 0.247 \) and 1504+357 at \( z = 0.673 \) the absorption takes place in the host galaxy of an AGN (Wiklind & Combes 1994, 1996b).

So far, 15 different molecules have been identified in these redshifted systems, plus many of their isotopomers, including complex, multi-atom molecules such as the cyclic species \( \text{C}_3\text{H}_2 \) (Combes & Wiklind 1999; Menten et al. 1999). The lines can be relatively broad, as for 1504+377 with a FWHM = 100 km s\(^{-1}\), or extremely narrow, as for 1413+135 (FWHM = 1 km s\(^{-1}\)). As opposed to emission studies, observations of redshifted absorption provide the ability to probe very narrow pencil beams through the intervening galaxy and, thus, given a sufficiently strong background source, to determine the physical and chemical conditions in single molecular clouds by observations of rare molecular species.

The best studied of the high-\( z \) molecular absorption line sources in terms of high resolution imaging is that associated with the gravitational lens system 1830–211 (Wiklind & Combes 1996a). At its redshift of 0.89, many of the ground level rotational transitions of molecules commonly found in galactic molecular clouds redshift into the observing bands of the VLA and the VLBA (Carilli et
Figure 1. The contour plot shows an image of the 'Einstein ring' radio source PKS 1830–211 at 43 GHz with a resolution of 0.1'' made with the Very Large Array. The spectra show molecular absorption by gas in the lensing galaxy, as observed with the Very Large Array toward the southwest radio component. Zero velocity corresponds to a heliocentric redshift of 0.88582.

al. 1997, 1998; Menten et al. 1999; see Fig. 1). Strong absorption is seen toward the SW radio component at $z = 0.88582$; e.g., the HCN $J = 1-0$ line has a peak opacity of 2.5 and FWHM = 25 km s$^{-1}$. The limit of 0.3 to the opacity toward the “tail” of the SW component implies an upper limit to the cloud size of 800 pc for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$. A VLBA image of the SW component at 24 GHz shows a core-jet structure extending $\approx 2$ mas to the northwest. Spectra of redshifted HC$_3$N $J = 5-4$ absorption at this resolution imply a lower limit to the cloud size of 2.5 mas, corresponding to 13 pc, although there may be sub-structure on scales of a few pc (Carilli et al. 1997, 1998). The implied upper limit to the volume averaged density is 1000 cm$^{-3}$, and the lower limit to the molecular mass is $3 \times 10^4$ M$_\odot$. This is consistent with a lower limit to the cloud size of 0.3 pc set by the fact that the line excitation temperatures are comparable to the microwave background (Frye et al. 1997).

Toward the NE component of 1830–211 weak molecular absorption is detected at a velocity of $-146$ km s$^{-1}$, where zero velocity is defined by the redshift ($z = 0.88582$) of the absorption seen toward the SW component. Here the HCN (1–0) optical depth is $\approx 50$ times smaller than for the zero velocity component observed toward the SW image (Wiklind & Combes 1998; Carilli et al. 1998). Chengalur et al. (1999) have detected both HI and OH absorption toward 1830–211. Interestingly, the HI absorption is stronger at $-146$ km s$^{-1}$ than at 0 km s$^{-1}$, implying an [HI/HCN] ratio differing by a factor of 125 between the two lines-of-sight, assuming equal spin temperature.
Menten et al. (1999) conclude that the molecular abundance ratios for the 1830–211 absorber are similar to values found for Galactic dark clouds and do not show the high abundances of HCO$^+$, HCN, and H$_2$CO relative to CO found in many diffuse clouds (Liszt & Lucas 1995). Moreover, they find [C$^{12}$]/[C$^{13}$] = 35, which is smaller by a factor of two than the value measured in the solar system and the local ISM, but comparable to that found in some inner Galaxy clouds. Since $^{13}$C is only produced in low and intermediate mass stars, while $^{12}$C is also produced in massive stars, this ratio is expected to decrease in time and with increasing stellar processing (Wilson & Matteucci 1992). Studying the deuterium chemistry of the 1830–211 absorber, Shah et al. (1999) set an upper limit of 0.003 on the [DCN/HCN] ratio. This is in the upper range of values seen in Galactic dense clouds, where the deuterium abundance in the molecular phase is greatly enhanced due to fractionation. Gerin & Roueff (1999) state that this DCN upper limit is barely compatible with a high gas phase deuterium abundance of $10^{-4}$, perhaps indicating significant astration (Shah et al. 1999).

A review of oxygen chemistry in 0218+357 is given in Combes & Wiklind (1999).

Overall, from detailed chemical modeling Gerin & Roueff (1999) conclude that the high column density, low density, low O$_2$ and DCN abundance, and high CCH abundance can be understood if the absorbing material is chemically in the High Ionization Phase (HIP), in which the fractional ionization is $\sim 10^{-6}$, the gas phase C abundance is high, and the chemistry is driven by charge transfer reactions with H$^+$. The HIP is the sole stable phase for molecular clouds at low densities ($< 10^4$ cm$^{-3}$).

The two known absorption systems associated with lensing galaxies in gravitational lens systems can be used to study the lens parameters. Wiklind & Combes (1998) and Combes & Wiklind (1999) discuss the potential of using single dish observations of the variation of molecular absorption line optical depths to measure the geometric time delay for 1830–211.

The observed difference in absorption velocities between the SW and NE images in 1830–211 allows for tight constraints on the lens mass distribution and, thus, lensing models. Wiklind & Combes (1998) derive $V_0 \approx 220\sqrt{D}$ km s$^{-1}$ for the rotation velocity, $V_0$, of the $z \approx 0.89$ lensing galaxy, with the “effective distance” $D$, in Gpc, in standard notation. Using the source redshift of 2.507 yields $V_0 \approx 366$ km s$^{-1}$, implying a massive early-type spiral lens. The centroid position, inclination angle, and orientation of the lens in this model are consistent with the observed values in HST near-IR imaging (Lehar et al. 2000).

An interesting use of redshifted molecular absorption lines is to constrain the evolution of the temperature of the microwave background radiation. The critical densities for collisional excitation of the lower rotational lines of high dipole moment molecules such as HC$_3$N are typically $\geq 10^5$ cm$^{-3}$. As the absorbing clouds seen toward 1830–211 are likely to have a lower density than this, one expects the molecular excitation for such molecules to be determined by the ambient radiation field, which, at $z = 0.9$, will be dominated by the microwave background radiation, at least outside of active star forming regions. Combes & Wiklind (1999) summarize single dish measurements of the excitation temperature for a number of molecules at $z = 0.88582$ toward 1830–211, while Menten et al. (1999) present perhaps the most accurate measurement based on VLA observations of the $J = 3–2$ and 5–4 transitions of HC$_3$N, from which they
derive $T_{ex} = 4.5^{+1.5}_{-0.6}$. This is consistent with the expected microwave background temperature of 5.14 K.

Drinkwater et al. (1998) and Wiklind & Combes (1998) show how a comparison of redshifts derived from molecular absorption to those derived from HI 21cm absorption constrains the cosmic evolution of the fine structure constant, $\alpha$. The current limits are not set by the accuracy of the measurements but by (possible) relative systematic motions of molecular and atomic absorbing clouds in galaxies. Most recently, Carilli et al. (2000) have used VLA observations to constrain sight-lines to sub-kpc scales, thereby removing at least one of the uncertainties in the problem. They set a limit of $|\alpha| < 3.5 \times 10^{-15} \text{ year}^{-1}$ to a look-back time of 4.8 Gyr, assuming that the velocity error is dictated by small scale ISM motions.

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ISOCAI M Deep Surveys and the Cosmic Infrared Background

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Abstract. The steep slope of the ISOCAI M 15 μm number counts indicates that infrared galaxies have strongly evolved since z ~ 1 − 1.5. A nearly complete spectroscopic sample of ISOCAI M galaxies in the Hubble Deep Field North (HDFN) shows that their redshift distribution is peaked around z ~ 0.8. We show that the 7 μm luminosity of local galaxies is correlated with their 8-1000 μm luminosity, and therefore star formation rate (SFR). We use this correlation in the rest-frame of the ISOCAI M galaxies to deduce their IR luminosities (~ 4 × 10^{11} L_{⊙}), SFR (~ 80 M_{⊙} yr^{-1}) and contribution to the peak of the cosmic IR background (CIRB) at 140 μm. We find that they most probably produce the bulk of the CIRB.

1. Introduction: Identification and Nature of the ISOCAI M Galaxies

In Elbaz et al. (1999) we showed that the ISOCAI M 15 μm differential counts were much steeper than expected if the 15 μm luminosity function was to remain identical from z=0 to larger redshifts. In the following, we discuss the identification and nature of the sources responsible for this evolution.

The ISOCAI LW3 or 15 μm band has a response which covers the range λ = 11.5 to 17 μm and is centered at 14.3 μm. The full width half maximum (FWHM) of the ISO point spread function (PSF) in this band is 4.6 arcsec. In the ultra-deep ISOCAI surveys the final pixel size is 2 arcsec (due to micro-scanning), which allows some oversampling of the PSF. In the HDFN proper, Pozzetti et al. (1998) measured a density of optical sources with I(AB)<29 of 529 sources per square arcmin (2819 objects over an area of 5.33 square arcmin). This corresponds to an average of 9 optical sources per ISOCAI beam. However, the identification of optical counterparts for the ISOCAI M 15 μm galaxies is strongly facilitated by the facts that:

- above a redshift of z ~ 1.5, the rest-frame emission of galaxies drops strongly (the dust emission becomes negligible below ~ 6 μm, except for AGNs).

- for the completeness limit of 0.1 mJy reached in the HDFN, only LIRGs (i.e. galaxies with L(8 − 1000 μm) ≥ 10^{11} L_{⊙}) are detected above z = 0.67 and ULIRGs (with L(8 − 1000 μm) ≥ 10^{12} L_{⊙}) above z = 1.25, if we assume that the correlation between the mid and far IR emission of galaxies observed in the local universe (see next Section) remains valid at z ~ 1.
Figure 1. (a): ISOCAM 15\(\mu m\) contour maps of the sources 20 \((z=0.961)\), 26 \((z=0.752)\), 30 \((z=0.557)\), 33 \((z=0.642)\), overlayed on the optical HDFN image (Aussel et al. 1999). (b): ISOCAM-CVF MIR spectra of 4 galaxies, normalized at 7.7 \(\mu m\), as a function of L(IR) (given on the right of the name).

This selection effect explains why the centroid of the isocontours of ISOCAM MIR sources nearly fall on a relatively bright optical galaxy, as shown by the contour maps on the Fig.1a. This effect is so strong that one can find back the astrometry (better than 2 arcsec) of the ISOCAM contours by matching the pattern of the ISOCAM galaxies with the one of the brightest optical galaxies in the field.

Among a total of 40 galaxies detected by Aussel et al. (1999) in the HDFN+FF above a flux density of 0.1 mJy (completeness limit), 36 have a spectroscopic redshift \((8/40\) are in the HDFN proper). Their flux densities range from 0.1 to 0.5 mJy, i.e. where most of the evolution is observed. At this redshift, the LW3 filter spans the rest-frame 6.2-9.2 \(\mu m\) wavelength range which is very close to the ISOCAM LW2 filter \((5-8.5 \mu m\), centered at 6.75 \(\mu m\)), hence we can use the correlation that we find between \(L(8-1000 \mu m)\) and \(L(6.75 \mu m)\) (Fig.2a) to estimate the IR luminosity and SFR of these galaxies. The results are summarized in the Fig. 2b. We find a median IR luminosity of \(L(8-1000 \mu m) \sim 3.6 \times 10^{11} L_{\odot}\) \((\text{for } \Omega_m = 0.3, \Omega_L = 0.7)\), and assuming that \(SFR = 1.7 \times 10^{-10} L(8-1000 \mu m)\) (Kennicutt 1998), we get a median SFR of about 80 \(M_{\odot}yr^{-1}\). We separate the contribution of 4 galaxy types as a function of IR luminosity in the Table 1.

2. Cosmic IR Background (CIRB)

The sum of the contribution of all individual galaxies detected by ISOCAM at 15 \(\mu m\) sets a lower limit to the 15 \(\mu m\) extragalactic background light (EBL) of \(IGL(15 \mu m) = 2.6 \pm 0.5 nWm^{-2}sr^{-1}\), down to 0.04 mJy. This integrated galaxy light is reduced to \(IGL(> 0.1mJy) = 1.6 \pm 0.3 nWm^{-2}sr^{-1}\), down to
0.1 mJy, if we do not include the small sample of galaxies corrected for lensing magnification by Altieri et al. (1999). More than 80% of this IGL comes from galaxies fainter than 0.5 mJy, typical of the flux densities found in the ISOCAM survey of the HDFN+FF. The bulk of the IGL(15 µm) is therefore produced by galaxies at a median redshift of $z > 0.8$, and the wavelength where the CIRB peaks (140 µm) corresponds to 80 µm in the rest-frame of the ISOCAM galaxies. L(80 µm), which is roughly equal to the mean of the IRAS L(60 µm) and L(100 µm), is almost exactly equal to L(8-1000 µm)/2. One can therefore estimate the 140 µm luminosity of the ISOCAM galaxies from the correlation shown in the Fig.1a. The results are shown in the Table 1 as a function of the galaxy type (i.e. IR luminosity).

In order to derive these values, we have assumed that the correlation between the far and mid IR luminosities remained valid up to $z=1.3$. We used the L(IR) versus L(LW2) correlation for galaxies at $z > 0.5$, i.e. whose 7.7 µm aromatic feature falls in the LW3 band, and the L(IR) versus L_{IRAS}(12 µm) at $z < 0.5$. The ISOCAM detection limit of 0.1 mJy was converted into a L(IR) with these two correlations (plain line in the Fig.2b). The discontinuity around $z = 0.5$ is due to the entrance of the 7.7 µm major aromatic feature in the LW3 band (see Fig.1b), i.e. at $z=0.5$ we use a different conversion factor to get L(IR).

We can see that if we use the IGL calculated down to 40 µJy, i.e. including lensing magnification, the ISOCAM galaxies produce an IGL at 140 µm of $23.4 \pm 4.6 \, nW m^{-2} sr^{-1}$, i.e. 94% of the value measured by DIRBE of $25 \pm 7 \, nW m^{-2} sr^{-1}$ (Finkbeiner, Davis & Schlegel 2000, Hauser et al. 1998, Lagache et al. 2000). If we only count galaxies above 0.1 mJy (no lensing), then the $\text{IGL}_{\text{CAM}}(140 \mu m) = 15.1 \pm 4.6 \, nW m^{-2} sr^{-1}$ ($60\%$ of $\text{EBL}_{\text{DIRBE}}(140 \mu m)$).

In order to use these correlations, we have assumed that the IR light radiated by ISOCAM galaxies was due to star formation and not accretion around a black hole. AGNs present flatter spectra, hence their FIR over MIR ratio is smaller, so the larger the AGN contribution, the smaller the $\text{IGL}_{\text{CAM}}(140 \mu m)$.
Table 1. Contribution of the ISOCAM 15 μm galaxies to the peak of the CIRB at 140 μm. Col.2 & 3 are the median redshift and 15 μm luminosity. Col.4 & 5 are deduced from the correlation shown in the Fig. 2 (right) assuming that the LW3-15μm luminosity corresponds to the rest-frame LW2-6.75μm luminosity (<z> = 0.8). Col.6 is the fraction of IGL produced by a given galaxy type and Col.7 is the contribution of these galaxies to the EBL(140μm), i.e. IGL(140μm).

<table>
<thead>
<tr>
<th>Type</th>
<th>&lt;z&gt;</th>
<th>&lt;L_{15μm}&gt; (L_⊙)</th>
<th>&lt;L_{IR}&gt; (L_⊙)</th>
<th>&lt;SFR&gt; (M⊙/yr)</th>
<th>%IGL</th>
<th>IGL_{CAM}(140μm) [nWm⁻²sr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULIRGs</td>
<td>1.0</td>
<td>9.3 × 10¹⁰</td>
<td>2.4 × 10¹³</td>
<td>410</td>
<td>40</td>
<td>13.4 ± 2.6</td>
</tr>
<tr>
<td>LIRGs</td>
<td>0.8</td>
<td>2.5 × 10¹⁰</td>
<td>3.8 × 10¹¹</td>
<td>64</td>
<td>42</td>
<td>7.7 ± 1.5</td>
</tr>
<tr>
<td>SBs</td>
<td>0.5</td>
<td>6.2 × 10⁹</td>
<td>8.5 × 10⁹</td>
<td>14</td>
<td>10</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>normal</td>
<td>0.1</td>
<td>3.0 × 10⁸</td>
<td>3.5 × 10⁹</td>
<td>0.6</td>
<td>8</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>Total</td>
<td>0.8</td>
<td>3.3 × 10¹⁰</td>
<td>4.5 × 10¹¹</td>
<td>76</td>
<td>100</td>
<td>23.9 ± 4.6</td>
</tr>
</tbody>
</table>

over IGL_{CAM}(15μm). A detailed study of the nature of the ISOCAM galaxies is still going on. However, we can already say among the 8 ISOCAM sources brighter than 0.1 mJy detected in the HDFN proper, 2 have been detected in the hard X-ray by Chandra (Hornschemeier et al. 2000), one of which is a spiral galaxy at z=0.089 (which X-ray emission may be due to a SN remnant). The other one (src 20 in Fig.2a) is clearly identified as an AGN, but was also clearly stated as such from the optical. It has also been detected in the LW2 band which implies a flat LW3/LW2 ratio typical of AGNs. This is the only galaxy detected both in LW3 and LW2 in the HDFN proper. If the fraction of AGNs is confirmed to be low among the ISOCAM galaxies then our IGL estimate is realistic. Then ISOCAM galaxies most probably produce the bulk of the cosmic IR background and their detailed study is of fundamental importance.

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References

Hidden Star Formation: The Ultraviolet Perspective

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Abstract. Many recent estimates of the star formation rate density at high redshift rely on rest-frame ultraviolet (UV) data. These are highly sensitive to dust absorption. Applying a correlation between the far-infrared (FIR) to UV flux ratio and UV color found in a local starbursts to galaxy samples out to $z \sim 3$, one can account for most of the FIR background. However, the correlation is based on a sample that does not include the most extreme starbursts, Ultra Luminous Infrared Galaxies (ULIGs). Our new UV images of ULIGs show that their FIR fluxes are underpredicted by this correlation by factors ranging from 7 to 70. We discuss how ULIGs compare to the various types of high-$z$ galaxies: sub-mm sources, Lyman Break Galaxies, and Extremely Red Objects.

1. Why observe star forming galaxies in the ultraviolet?

About 60% of the intrinsic bolometric luminosity of star forming populations is emitted between 912Å and 3000Å with little variation in this fraction with star formation duration (from models of Leitherer et al. 1999). Hence UV light is potentially very useful for measuring star formation. It represents direct emission from hot main-sequence stars, the same stars that will provide the majority of the mechanical energy feedback into the ISM. The UV spectrum is very rich in features that can be used to diagnose the stellar populations and intervening ISM. The overall intrinsic spectral slope in the UV is fairly constant. For young ionizing populations it is set by the Rayleigh-Jeans tail of the Planck
Hidden Star Formation: The UV perspective

function. When looking at high redshifts the importance of the rest-frame UV increases; at a fixed bandpass it is the last stop before the Lyman-edge.

The big problem with using UV measurements is dust, which most efficiently absorbs and scatters UV radiation. The absorbed UV light is reradiated at far infrared (FIR) wavelengths. Not only is the amount of dust important, so to is its distribution. If the geometry is unfavorable, as in the mixed stars and dust model, then the UV emission will be dominated by the stars closest to the observer and the center may be practically invisible (e.g. Witt, Thronson, & Capuano 1992). Fortunately, this is not the case for a wide range of starburst galaxies as shown in Fig. 1. For them the FIR to UV flux ratio, or infrared excess (IRX), which gives the effective dust absorption, correlates with the UV spectral slope $\beta$ (Meurer et al. 1995, 1999). This is a prediction of the dust screen model (Witt et al.). While variations on this geometry can also explain this correlation (Calzetti 1997; Charlot & Fall 2000), the mere fact of this correlation allows one to recover the intrinsic luminosity of starbursts using UV quantities alone.

2. Applying IRX-$\beta$ to the high-redshift universe

Lyman Break Galaxies (LBGs) at $z \sim 3$ are similar to local starbursts. In particular they have similar SEDs (Dickinson 2000), spectral properties (Tremonti et al. 2000), ISM dynamics (e.g. Pettini et al. 1999), and surface brightnesses (Meurer et al. 1997). They are also noticeably redder than dust-free starbursts. Meurer et al. (1999) used the rest frame colors of LBGs and the IRX-$\beta$ correlation to estimate that the Hubble Deep Field LBG sample suffers from a factor of about five in dust absorption at rest $\lambda_0 \approx 1600\,$Å. It is hard to test whether the IRX-$\beta$ correlation actually holds for LBGs because predicted FIR fluxes are typically just below current detection limits with instruments such as SCUBA. Other data show that what little we know about the LBGs is consistent with them obeying the same reddening law as local starbursts. For instance, we assumed that the FIR-radio correlation holds, and took the LBGs with the top ten predicted FIR emission and predicted summed radio fluxes of $27 \pm 5\,\mu\text{Jy}$, and $105 \pm 24\,\mu\text{Jy}$ (assuming a 0.3 dex uncertainty on each flux) at observed frame wavelengths 3.5cm and 20cm, while the Richards (2000) data yield measured summed fluxes of $28 \pm 10\,\mu\text{Jy}$, and $100 \pm 33\,\mu\text{Jy}$ respectively. Adopting IRX-$\beta$, Adelberger & Steidel (2000) show that the UV detectable galaxies at $z = 1, 2$ and 3 can account for most or all of the FIR background at 850 $\mu\text{m}$.

This rosy view of the utility of UV astronomy flies in the face of what we have learned over the last few decades: that dust enshrouded star formation is best seen in the infrared. Would not dust obstruct our view of star formation, even at high-$z$? The bright SCUBA sources, in particular, are inferred to have $z \approx 1 - 3$, usually have little or no rest-frame UV emission and probably have an equal contribution to the star formation rate density as non-dust corrected LBGs (Barger, Cowie, & Richards 2000). They have $L_{\text{UV}} > 10^{12}\,L_{\odot}$, so the best local analog to them are thought to be the Ultra-Luminous Infrared Galaxies (ULIGs). Relatively little was known about the UV properties of ULIGs, until Trentham, Kormendy & Sanders (1999) presented weak UV detections of three ULIGs with HST’s Faint Object Camera and Surace & Sanders (2000) showed that they are detectable from the ground in the $U'$ band.
Figure 1.  (Left) The IRX = $F_{\text{FIR}}/F_{\text{UV}}$ versus $\beta$ relationship of local starbursts observed by IUE (Meurer et al. 1999). Here the UV flux is measured at $\lambda_0 = 1600\,\AA$, and the left axis converts IRX to the effective absorption $A_{1600}$ in magnitudes.

Figure 2. (Right) The IRX-$\beta$ plot for ULIGs (triangles) in relation to the IUE starbursts. Here $\beta$ and the UV flux are measured photometrically through the actual or synthetic STIS bandpasses.

3. STIS UV Images of ULIGs

We have been granted HST time to image seven galaxies in the UV using the STIS (Space Telescope Imaging Spectrograph) MAMAs which have much higher sensitivity than the FOC. Our sample was chosen to have $\log(L_{\text{bol}}/L_{\odot}) \geq 11.6$, starting in $L_{\text{bol}}$ where the IUE sample ends. So far six galaxies have been observed, five of these are ULIGs. We detect all of these in both the far UV (FUV; $\lambda_c \approx 1460\,\AA$) and near UV (NUV; $\lambda_c \approx 2350\,\AA$). In both bands, UV emission can be detected projected to within 1 Kpc of the infrared nuclei seen by NICMOS (Scoville et al. 2000). However, especially in the FUV, very little, if any UV emission is detected within the inner few hundred parsecs where most of the bolometric luminosity probably originates.

Figure 2 shows the IRX-$\beta$ diagram for our sample compared to the IUE starbursts. Typically only 0.5% of the bolometric luminosity is observed in the FUV. Furthermore, the IRX-$\beta$ correlation under-predicts the FIR emission of ULIGs by factors ranging from 7 to 70. The FIR flux is still under-predicted if only the light within 1 Kpc of the IR nucleus is considered. In these galaxies IRX-$\beta$ only gives a lower limit to the FIR flux. These results confirm that ULIGs represent galaxies with star formation almost totally hidden from the UV.

4. High-$z$ Implications

Our work shows that we must still be cautious with rest-frame UV observations of galaxies: they may harbor hidden-star formation beyond that predicted with the IRX-$\beta$ correlation. However, not all galaxies are as extreme as ULIGs. At
high-z, the most luminous LBGs can not generally have IRX values like ULIGs or else more would be detected at 850µm with SCUBA (multiply predictions in Table 4 of Meurer et al. 1999 by 7–20). Could ULIGs be selected as LBGs? At $z = 3$ ULIGs would have an observed frame $V - I \leq 0.5$ ABmag. Presumably they would have very red $U - B$ colors resulting from the strong opacity of the Lyman forest and edge. Therefore, they should have the right colors to be selected as LBGs. However at this redshift they would be very faint, having $V \sim 27$ to 30 ABmag, at or beyond the limits of many current surveys such as the Hubble Deep Fields. So ULIGs still make good analogs to SCUBA sources, but probably only contribute to the faint end of the LBG population.

ULIGs have also been touted as good local prototypes for Extremely Red Objects (EROs). Using our photometry and published results we find that ULIGs emit enough rest-frame UV emission, that at $z = 1.8$ or 3.5 in the observed frame they would have $2.3 < R - K < 5.6$ ABmag. This is bluer than $R - K < 6$, the definition of EROs (Graham & Dey 1996). Since our sample is small, and some approach this limit perhaps some more extreme ULIGs may be recognized as EROs at high-z, but in general they would be too blue.

References

Prospects for future far-infrared/submillimeter studies of the high-redshift Universe

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Abstract. Observations made using COBE, SCUBA, ISO and MAMBO have provided a reasonable working knowledge of both the intensity of the submm and far-infrared background radiation and the source counts of luminous high-redshift dusty galaxies. However, because there are uncertainties in the background intensity determinations, the samples of detected galaxies are small, and most importantly, their redshift distributions are very incomplete, details of the evolution of dusty galaxies remain unresolved. The next steps forward in the field will be the launches of SIRTF and ASTRO-F, the commissioning of SOFIA and new, more capable ground-based mm/submm-wave cameras – BOLOCAM, SHARC-II and SCUBA-II – the use of ultra-long duration balloon experiments, such as BLAST, the construction of ALMA and the arrival of FIRST, and ultimately the advent of space-borne far-infrared interferometers, such as SPECS. There are also exciting prospects for direct mm/submm-wave CO-line redshift surveys using wide-band spectrographs. Using these new facilities, the number of high-redshift dusty galaxies known will be increased dramatically. Spectroscopy using SIRTF, SOFIA and FIRST will probe the astrophysical processes within these sources in detail, hopefully addressing the open question of the fraction of the counts and background radiation that is generated by the formation of high-mass stars and by active galactic nuclei (AGNs). The spatial and spectral structure of distant dusty galaxies will finally be resolved in detail using ALMA and SPECS.

1. Introduction

The determination of the intensity of extragalactic background radiation in the submm and far-infrared wavebands has been a very important development in observational cosmology (Puget et al. 1996; Hauser et al. 1998; Schlegel, Finkbeiner & Davis 1998; Finkbeiner, Davis, & Schlegel 2000). Over the same period, the first observations that were sufficiently deep to detect high-redshift galaxies in the mm, submm and far-infrared wavebands were made using the 1.25-mm MAMBO bolometer camera at the IRAM 30-m telescope (Bertoldi et al. 2000), the 450/850-µm SCUBA camera at the JCMT (Smail, Ivison, & Blain 1997; for a current summary see Blain et al. 2000a) and the PHOT instrument aboard ISO (Kawara et al. 1998; Puget et al. 1999; Juvela, Mattila, & Lemke 2000). Most of the results for both counts and background have been summarized elsewhere, see for example Figs 9 and 12 in Blain et al. (1999b).
Progress has been rapid: not only has the background radiation spectrum been determined for the first time, but most of the 850-μm background radiation, and about 30% and 10% of the background at wavelengths of 450 and 175 μm respectively has been accounted for as coming from individual detected galaxies.

This progress has been possible only because of tremendous improvements in the sensitivity and field of view of instruments in these wavebands. Many instrumental references can be found in Blain (1999a); to save space in this brief article they are generally not repeated here. The important pieces of missing information and the prospects for future developments of observations in the mm, submm and far-infrared wavebands are discussed below.

2. Key missing information – redshifts of submm-selected galaxies

The mm–far-infrared background radiation spectrum is generated by thermal emission from interstellar dust in all the galaxies that lie along the line of sight, right back to the epochs when the first dust was formed during the early process of galaxy formation. It potentially includes emission from redshifts beyond recombination, as a neutral Universe is transparent to long-wavelength radiation. The intensity and spectral shape of the background radiation provides information about the volume emissivity, intrinsic spectral energy distribution and redshift of dusty galaxies; however, this information is not unambiguous. The counts of galaxies that make up the brighter fraction of the population contributing to the background can be used to refine and confirm the results of analyses of the background spectrum, but unfortunately neither the values of these quantities nor different scenarios of galaxy evolution can be distinguished strongly. Indeed, from the background and count data alone, the median redshift of galaxies detected in deep SCUBA images at 850-μm could plausibly lie between 1 and 5. In order to discriminate between different well fitting models, measurements of redshift distributions are necessary; determinations of accurate counts at other mm/submm wavebands are useful, but less important. For more details see Blain et al. (1999a,b).

Unfortunately, the redshift distribution of SCUBA galaxies is hard to determine for two reasons. First, it is difficult to identify counterparts for submm-selected galaxies in other wavebands because their positions are relatively uncertain. The JCMT beam is 15 arcsec wide, and so the centroids of even the most significant detections are uncertain to within several arcseconds. Secondly, counterparts are reasonably expected to be extremely faint, perhaps so faint that optical spectroscopy will remain challenging until NGST is available (Smail et al. 2000).

Deep radio observations are very useful for finding the positions of counterparts (Ivison et al. 1998; 2000). The flux density ratio between the submm and radio wavebands can also be used to provide an indication of redshift (Carilli & Yun 1999, 2000; Smail et al. 2000; Barger, Cowie, & Richards 2000). Note however that the result is offset to lower values by the presence of any radio emission from a buried AGN, and depends on the dust temperature in the galaxy (Blain 1999b), with hotter galaxies at higher redshifts being difficult to distinguish from cooler ones closer by. Observations of high-resolution dust emission using mm-wave interferometer arrays can also be used to obtain better
positions (Downes et al. 1999; Frayer et al. 2000; Gear et al. 2000); however, accurate relative optical-mm astrometry may be difficult in the absence of deep radio data because of the small fields of both the optical and mm-array images.

To confirm an identification beyond reasonable doubt, it is necessary to obtain an optical/near-infrared redshift for the candidate and then detect CO line emission at the same redshift and position. However, this is a slow process and an accurate redshift is essential. So far only three submm-selected galaxies have been observed in this way (Frayer 1998, 1999; Kneib et al. in prep), less than 10% of those described in the literature. Future wide-band mm and submm spectrographs will improve this situation.

3. Future progress

At present, the SCUBA camera detects sources at the rate of about one per 8-hour shift at the JCMT. Within the next few years, new large-format mm- submm cameras on ground-based telescopes – including BOLOCAM for the CSO/50-m LMT, SHARC-II (Dowell, Moseley, & Phillips 2000) for the CSO and SCUBA-II for the JCMT – will offer more rapid detection rates and access new wavebands. At shorter wavelengths, the MIPS instrument onboard SIRTF, the HAWC camera aboard SOFIA and balloon-borne instruments such as BLAST (Devlin et al. 2000) will provide similar improvements over existing surveys. The simple increase in the detection rate of galaxies will assist follow-up studies by providing larger samples of objects to sift. In addition, the higher spatial resolution of images – from SCUBA-II at 450 µm, SHARC-II at 350 µm, and BOLOCAM at 1.1 mm on the LMT – will make the identification process easier. Wider survey fields and greater numbers of detections will allow large-scale statistical studies of the distribution and clustering of high-redshift dusty galaxies to be carried out (Halman & Knox 2000).

There are also excellent prospects for more rapid detection of redshifted CO emission from candidate galaxies, mainly by increasing the bandwidth of instruments from the current maximum of 4 GHz to several 10’s of GHz. This will be sufficient to yield a realistic chance of detecting simultaneously adjacent CO lines – separated by 115/(1 + z) GHz in the observer’s frame for a galaxy at redshift z – from a submm-selected galaxy, and so determine a redshift without requiring optical observations (see Blain et al. 2000b; Blain 2000).

In the longer term, the ground-based ALMA interferometer array and space- borne mid- and far-IR interferometers such as SPECS will provide wide spectral coverage, sub-arcsec spatial resolution and great sensitivity. Using these instruments the detailed astrophysics within distant dusty galaxies will be resolved in detail. However, interferometers have small fields of view. Wide-field surveys made using the FIRST and Planck Surveyor space missions will be required provide extensive lists of targets, in addition to the legacy of observations left by surveys made using SIRTF and ASTRO-F (Takeuchi et al. 1999).

4. Summary

A wide range of new instruments for studying the evolution of galaxies in the mm, submm and far-infrared are proposed and under construction. Observa-
tions using these facilities will enhance significantly the size and spatial resolution of catalogs of galaxies selected in these wavebands, and the amount of spectroscopic information available. The goal of understanding the history of dust-enshrouded galaxy formation and evolution in detail by determining the redshift distributions of galaxies selected in these wavebands will be realized.

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References