AST/RO Observations of Neutral Atomic Carbon

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Abstract. The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), a 1.7 m aperture submillimeter-wave dish, began operations at the South Pole in January 1995. The telescope's primary target is the 492 GHz transition of neutral atomic carbon [C I]. Neutral carbon is an important new probe of the previously unexplored dense atomic phase of the interstellar medium. Because of the unparalleled transparency of the Polar atmosphere in the submillimeter, AST/RO can make high sensitivity observations in the [C I] line throughout most of the winter season. We discuss here a few AST/RO [C I] studies: (1) measurements of the [C I] scale-height and galactic latitude distribution; (2) the first detection of [C I] in the Magellanic Clouds; (3) detection of 8 translucent molecular clouds at high Galactic latitudes, (4) a survey of 70 H II regions in or near the Galactic plane, and (5) the detection of [C I] in absorption toward the Galactic Center, which suggests that the dense atomic phase of the ISM is pervasive.

1. Neutral Carbon in The Interstellar Medium

The earliest stars formed from a pristine interstellar medium with no elements heavier than helium. After galaxies formed, their stars formed heavier elements in their cores which were returned to the interstellar medium through winds and supernova explosions. As new stars formed from the metal-enriched gas and subsequently exploded, the interstellar medium contained more and more heavy elements. Because these heavy elements play an essential role, the formation of stars, of planets, and ultimately, of life, is intimately tied to the cycling of material back and forth between stellar interiors and the interstellar medium. The physics of the interstellar medium and its interaction with the stars that it spawns is thus a central problem in modern astrophysics.

Perhaps the most important element heavier than helium is carbon. Carbon is the fourth most abundant element in the universe and an important component in the chemistry and cooling of the interstellar medium of the Milky Way and other galaxies. Current observing techniques now permit observation of all phases of carbon in the interstellar medium: carbon in dust grains (graphite), molecular carbon (CO), neutral atomic carbon ([C I]), and ionized carbon ([C II]).

This is not the case for any other common element. Consequently, observations of carbon reveal the complete range of physical conditions found in the interstellar medium.

The ^{3}P electronic ground state of neutral atomic carbon is split by spin-orbit coupling into three levels, with energy differences of 23.6 K and 62.4 K, respectively. The resulting $^3\mathrm{P}_1$ to $^3\mathrm{P}_0$ magnetic dipole transition is at a frequency of 492.1607 GHz (609 μm), and the $^3\mathrm{P}_2$ to $^3\mathrm{P}_1$ transition is at a frequency of 809.345 GHz (370 μm). These fine-structure transitions are easily excited by collisions at the gas temperatures characteristic of the denser phases of the interstellar medium. Although carbon in dust (graphite) and molecular forms of carbon (CO) are routinely observed from the ground, atomic carbon observations are quite difficult because water vapor in the atmosphere makes it nearly opaque to their submillimeter spectral lines except at the very driest sites. The South Pole is by far the best submillimeter site characterized (Lane 1998), and CARA's AST/RO telescope is the first to observe neutral atomic carbon routinely and almost continuously.

Observations of neutral carbon are important to understand the interaction of starlight with the interstellar medium. When an O or B star forms, it emits copious amounts of far-ultraviolet (FUV, 6 to 13.6 eV) radiation. These FUV photons impinge on the surfaces of neutral clouds and are sufficiently energetic to eject electrons from dust grains. Through collisions with atoms and molecules, the photoelectrons heat the gas which in turn results in excitation of neutral and ionized carbon. Regions where FUV radiation dominates the heating are called *photodissociation regions* (PDRs).

Over the last ten years, chemical and thermal models of PDRs have been developed (e.g., Tielens and Hollenbach 1985; Hollenbach, Takahashi, & Tielens 1991) which predict the intensity of emission lines from these regions as a function of cloud density and incident FUV flux. These models show that neutral carbon is the by-product of the equilibrium of two competing processes taking place in the envelope of a molecular cloud: the photodissociation of CO, which creates C^0, and the photoionization of C^0, which destroys it to create C^+. The [C I] fine structure ($^3\mathrm{P}_1 \rightarrow ^3\mathrm{P}_0$) and ($^3\mathrm{P}_2 \rightarrow ^3\mathrm{P}_1$) lines at 609 μm and 370 μm are thus tracers of the transition between C^+ (the photodissociation region) and CO (the dense molecular cores). In PDRs with densities in the range 10^2 to 10^5 cm^{-3}, the models predict "the ubiquitous presence of [C I] emission" (Hollenbach et al. 1991).

To understand photodissociation regions, and to explore the distribution and properties of atomic carbon throughout the ISM, we deployed the AST/RO telescope to the South Pole in late 1994. We discuss some of the scientific results from the AST/RO telescope.

2. The Instrument

AST/RO is a 1.7 m diameter off-axis telescope for research in astronomy and aeronomy at wavelengths between 200 and 2,000 μm. It was installed at the South Pole during the 1994-95 Austral summer (Lane & Stark 1996). The instrument now operates with four heterodyne receivers and three acousto-optical spectrometers (AOSs). AST/RO's beamsize is about $110''(\lambda/600\mu\mathrm{m})$. This beamsize is large enough to allow large-scale mapping programs, yet is small enough to map distant clouds in the Galaxy and to just resolve nearby external galaxies.

All of the optics in AST/RO are offset to produce high beam efficiency and to avoid inadvertent reflections and resonances (Stark et al. 1997). The primary reflector is made of carbon fiber and has an rms surface accuracy of about 9μm. In its current configuration, AST/RO has a Coudé focus. The telescope also has a Nasmyth focus which is almost identical in its optical properties to the bent Cassegrain focus on NASA's Kuiper Airborne Observatory.

There are currently four heterodyne receivers mounted on an optical table suspended from the telescope structure in a spacious, warm Coudé room:

1. *230 GHz SIS receiver:* 325 K SSB noise temperature.
2. *460-500 GHz Schottky-barrier diode receiver:* 950 K DSB noise temperature. This receiver will work without a liquid Helium supply.
3. *460-492 GHz SIS waveguide receiver:* 200 K DSB noise temperature.
4. *460-492 GHz SIS quasi-optical receiver:* 165 K DSB noise temperature (Zmuidzinas & LeDuc 1993; Engargiola, Zmuidzinas, & Lo 1994).

The spectrometers currently available are two 1.1-GHz wide AOSs, each with 2048 channels, and one 63-MHz wide 2048 channel high-resolution AOS (Schieder, Tolls, & Winnewisser 1989). The entire system is highly automated to reduce to a minimum the need for human intervention; we have successfully operated AST/RO from Boston over the Internet. Nonetheless, an astronomer will always be wintering over with AST/RO in order to provide the support needed to conduct successful observations.

The AST/RO telescope was designed by PI Antony Stark of the Smithsonian Astrophysical Observatory (Stark et al. 1997) and fabricated between 1990 and 1992 at the Scientific Instrument Facility at Boston University and at Bell Laboratories in Holmdel, New Jersey. All the components of AST/RO were integrated and installed at a test site at Boston University, where in 1993 and 1994 the system was used for observations at 230 GHz and tests at 492 GHz (Stark et al. 1994).

AST/RO was designed with a fourfold purpose:

1. Scientific study of submillimeter-wave lines from the Milky Way and nearby galaxies,
2. Measurements of mesospheric and stratospheric lines from molecular species in the Earth's atmosphere,
3. Tests of the South Pole as a submillimeter-wave observatory site,
4. Demonstration of the feasibility of operating a submillimeter-wave observatory during Austral winter, as a prototype for future South Pole telescopes.

Submillimeter site testing at the South Pole is reviewed in this volume by Lane (1998), and future South Pole telescopes are discussed by Stark (1998).

3. Science

3.1. The structure of the Milky Way

The distribution of [C I] with Galactic latitude reveals the scale height of photodisssociated material throughout the Galaxy. A priori, it is not clear that molecular material traced by CO and more diffuse photodissociated material traced by [C I] should have the same scale-height. To measure the [C I] scale-height directly, several [C I] "b-strips," cross-cuts through the Galactic plane at specific Galactic longitudes, have been made with AST/RO (Lane et al. 1998, in preparation). To date, we have obtained 2 high-quality b-strips at $l = 336.4$ and $l = 330$. When compared with CO J=1-0 b-strips at similar longitudes from Bronfman et al. (1989), there is a striking correlation between the [C I] and CO clumps. Because AST/RO would have detected much fainter CI emission, apparently there is little or no significant CI emission outside of CO-emitting molecular clouds. This result suggests that CI arises primarily in the photodissociated skins of molecular clouds, and that there are few clouds that emit CI but not CO.

3.2. Neutral carbon in absorption

AST/RO has made the first detection of the 492 GHz [C I] line in absorption (see Fig. 1; Staguhn et al. 1997). This absorption feature at $v_{lsr} = 12$ km s^{-1}, which is observed over a region at least $5'$ across in the direction of Sgr C, allows the derivation of lower limits for the [C I] column density in cold foreground material in the Galactic disk.

The observations have been compared with ^{12}CO, ^{13}CO, and HCO^+ data from other telescopes to determine the temperature and abundance ratio of [C I] to CO in the foreground gas (Staguhn et al. 1997). Comparison of the absorption data with the low-resolution COBE FIRAS [C I] emission line survey in the Galactic plane indicates that a substantial fraction of the atomic carbon in the interstellar medium has very low excitation ($T_{ex} < 10$ K) and thus may be difficult to detect in emission.

3.3. High latitude clouds

A high-latitude cloud (HLC) is a nearby, low-mass molecular cloud that lies at high Galactic latitudes. These objects typically contain only a few hundred solar masses. Because their visual extinctions are close to 1 magnitude, photochemistry and photodissociation dominate their composition and structure. In fact, these clouds represent the transition between atomic and molecular clouds. Because they are nearby and contain no embedded UV sources, they are excellent laboratories to study photoprocesses.

To study photodissociation in these simple clouds, a CI survey of nearby high-latitude clouds was undertaken with AST/RO (Ingalls et al. 1997). Of the 15 southern high-latitude clouds (HLCs) listed by Keto and Myers (1986), eight have been observed by AST/RO in the [C I] line and all eight were detected (see Fig. 2 in Ingalls et al. 1998). Apparently, [C I] emission is ubiquitous among the HLCs. The C/CO column density ratio in these objects ranges from 0.4 to 2.5; some of these clouds are more easily seen in [C I] than in CO. The measured abundances of C and CO in the HLCs can be explained by a simple model

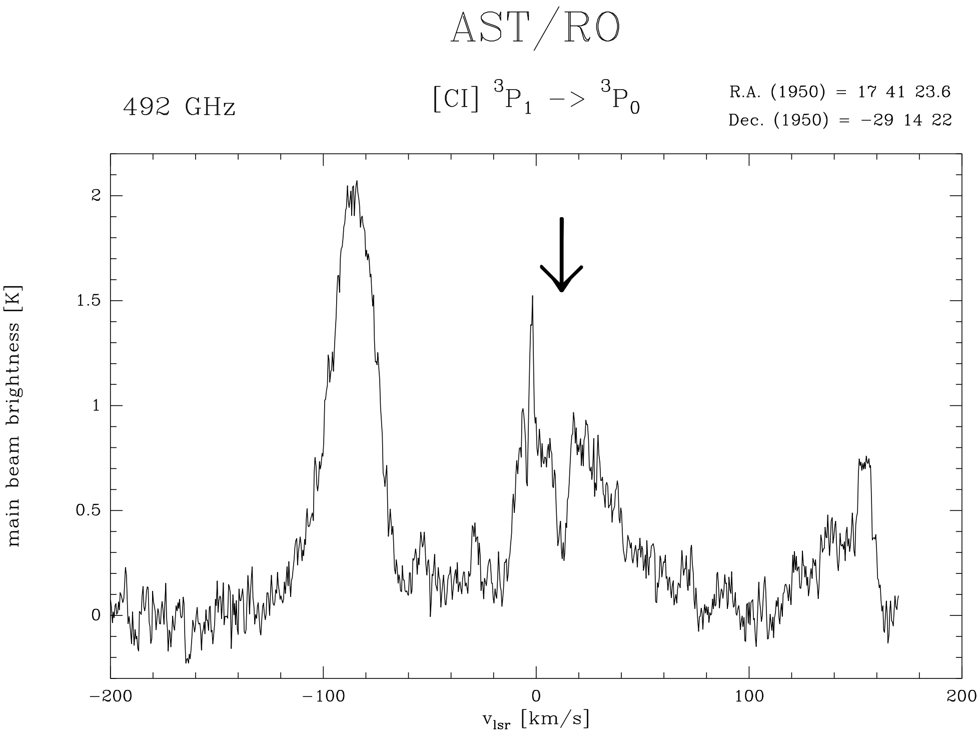

Figure 1. **AST/RO Detection of [CI] Absorption Toward the Galactic Center** The 492 GHz [C I] line in the direction of Sgr C ($\alpha_{1950} = 17^{\rm h}\ 41^{\rm m}\ 23^{\rm s}.6$, $\delta_{1950} = -29^\circ\ 14'\ 22''$), from Staguhn et al. (1997). The baseline has been determined by spectrometer channels beyond the range of this plot. Most of the emission with $|v_{\rm LSR}| <$ 160 km s^{-1} arises in the Galactic Center region 8 kpc distant and has the characteristic broad linewidths ($FWHM > 25$ km s^{-1}) of Galactic Center gas. Superposed on the emission at $v_{\rm LSR} = 12$ km s^{-1} is a relatively narrow ($FWHM \sim 8$ km s^{-1}) absorption line which arises in a number of translucent foreground clouds at a distance of $\sim$2 kpc. The excitation temperature of this gas is ~ 5 K, and its column density is at least a factor of two higher than the mean column density of the relatively higher excitation ($T_{ex} \sim 20$ K) material observed toward $|l| \approx 30^\circ$ by COBE (Staguhn et al. 1997).

of a homogeneous cloud with a diffuse far-ultraviolet radiation field incident on its surface (Ingalls et al. 1997). The observations of [C I] in these objects confirm that the HLCs are translucent objects, in which the atomic-to-molecular transition dominates the chemistry and structure. Further details of this study appear in this volume (Ingalls et al. 1998).

3.4. Magellanic Clouds

The interstellar medium in low metallicity systems has profoundly different properties than those of normal metallicity systems (e.g., Israel 1988, Maloney 1990). Due to the lack of dust-shielding and self-shielding, PDRs are expected to be much larger and more prominent in a low-metallicity ISM. Only in the densest molecular cores can CO molecules survive, and the rest of the molecular cloud, normally traced by CO in a high-metallicty ISM, will be entirely photodissociated.

This expectation is borne out by the faintness of CO emission from metal-poor dwarf galaxies (e.g., Tacconi & Young 1987; Ohta, Tomita & Saito 1993 Cohen et al. 1988; Israel et al. 1993; Rubio, Lequeux, & Boulanger 1993), as well as the brightness of [C II] emission from these same galaxies (Poglitsch et al. 1995, Israel et al. 1996). Indeed, the [C II]/CO luminosity ratios for H II regions in the LMC are larger than those in star-forming regions in the Milky Way by a factor of ~ 5 for N160 and a factor of ~ 50 for 30 Doradus (Israel et al. 1996). In other words, much of the Large Magellanic Cloud's ISM seems to be a vast photodissociation region.

The enhanced photodissociation regions in low-metallicity systems led us to expect that [C I] intensities are also enhanced in metal-poor environments. AST/RO recently made the first detection of [C I] emission from a low-metallicity system (Stark et al. 1997). The line was detected toward two positions in the LMC: N159, the star-forming region with the brightest CO ($J=1 \rightarrow 0$) emission in the LMC, and 30 Doradus, the brightest H II region in the local universe. As expected, [C I] emission is enhanced in the LMC (Stark et al. 1997). Toward N159, both the [C I]/CO and [C I]/^{13}CO intensity ratios are ≥ 2 times larger than measured for the Milky Way by COBE and in Orion. More details of this work, and new observations of the LMC with AST/RO can be found in this volume (Bolatto et al. 1998).

3.5. Star formation in the Milky Way

Because photodissociated material is most prominent near OB stars, AST/RO has conducted a [C I] survey of southern H II regions that mark the photoionized material surrounding OB stars. A sample of about 70 H II regions was selected from the catalog of Wilson et al. (1970) to be compact enough for the AST/RO telescope beam to encompass them entirely.

[C I] emission was found toward the position of every H II region. Indeed, in addition to finding a [C I] feature whose velocity matched that of the H II region, one or more additional features at unrelated velocities were often found. These features arise from photodissociated material in clouds throughout the Milky Way, and their presence confirms that PDRs pervade the Galaxy. More details of the H II region [CI] survey can be found in this volume (Huang et al. 1998).

4. Summary

The AST/RO telescope now routinely observes neutral carbon lines from the South Pole. AST/RO has detected neutral carbon from photodissociated material in diverse environments that span a broad range of UV field strengths, column densities, and metallicities. These studies are changing our understanding about the composition of the interstellar medium and its interaction with starlight.

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