Ay 192 **Principles of Astronomical Measurement**

Observational Limits, Observational Phase Space

I. What is the "phase space" of astronomical observations?

As mentioned in the introduction, observational astronomy is slightly differerent from many other "experimental" sciences because we generally cannot experiment directly on the objects we wish to study. Astronomical observations, except in the case of solar system astronomy, which now falls more into the fields of geology and space science, are limited to observing radiation from distant objects.

The properties of that radiation that we can study include intensity, spectral intensity, position, polarization and, in many cases, the time derivatives of those properties, such as proper motions and spectral variability. Signals are also affected and/or limited by distance and by intervening material — external signal degredation.

In addition, there are other limitations that should be considered when contemplating observing a celestial source, some trivial and some not so trivial. Examples of some of our fundamental observational limits have been described by M. Harwitt in *Cosmic Discovery*, a book about the limits of same. While Harwitt's thesis that there are only a small number of discoveries yet to be made in astronomy is probably not correct, his discussion of observational limits does serve as a useful guide to thinking about the observations that may be necessary to solve astrophysical problems.

In terms of observables in astronomy and astrophysics, then, we are back to

Photon Property	Phase Space
Energy	Frequency/Wavelength
Number	Intensity/Brightness
Arrival Time	Time Resolution
	Spectral Resolution
Angular Coordinates	Spatial Resolution
Spatial Coordinates	Position
	Proper Motion
Spin	Polarization

For any given photon, we have wavelength, spin, arrival time, α and δ (or whatever your favorite coordinsate system is).

Other useful references include:

Achinstein, P. & Hannaway, O. 1985, *Observation, Experiment, and Hypothesis in Modern Physical Science.*

There are many additional references in the philosophy of science on observables and the testing of hypotheses.

II. Observational Limits

What are the fundamental observable limits? We cannot observe

• 1. Photons whose energy, $h\nu$, is greater than the energy content of the Universe.

• 1a. Photons that are destroyed or absorbed before they get to us.

This includes very long wave radio waves which cannot pass through the ionosphere and are also absorbed by ionized gas in the Milky Way, and very high energy photons which are either scattered off the Galactic synchrotron background ($\lambda \leq 10^{-22}$ cm) or off the Cosmic Microwave Background ($\lambda \leq \sim 3\times10^{-19}$ cm) and produce electron-positron pairs. This last cutoff limits the distance out to which one can see very high energy Gamma Rays because photons at energies higher than $\sim 10^{15}$ ev are expected to scatter and pair produce off the diffuse CMB photons.

The effective upper limit on photons can be estimated from the requirements for conservation of energy and momentum. To produce an e^-/e^+ pair requires a rest energy of $\sim$ 1 Mev, and the average energy of a CMB blackbody photon is only $\sim 10^{-3}$ ev. So for pair production to occur, the high energy photon must have energy at least

$$h\nu \ = \ hc/\lambda \ \sim \ 2.5 \times 10^{14} ev$$

or a wavelength of 4×10^{-11} Å or 4×10^{-19} cm.

There is also a similar limit on the highest energy Cosmic Rays that should be observable. The Griesen-Kuzmin-Zatsepin or GKZ limit for high energy Cosmic Rays also results from the effects of scattering off CMB photons, but here the proton-photon scattering causes energy losses by pion production. The cross section for such scattering is very high at high energies, and Griesen and Zatsepin & Kuzmin predicted that CR's with energies above 5×10^{19} ev would be essentially unobservable unless they were produced locally.

Both these limits also have their "limits." There have been Cosmic Rays observed at energies approaching 10^{21} ev (not very many) and TEV Gamma rays have been succesfully detected from BL Lac objects out to redshifts of $\sim$ 0.05. The long wavelength limit is also determined to some extent by local absorption and noise. Ask Irwin for an update on the longest wavelength radio observations!

Griesen, K. 1966, PRL 16, 748.

Zatsepin, G. & Kuzmin, V. 1966, Pisma Zh. Eksp. Theor. Fiz. 4, 114.

• 2. Spectral resolutions greater than the natural line widths (typically R = 10^8 in the optical), or the expected doppler or thermal widths.

The natural line width is a property of the Heisenberg Uncertainty Principle,

$$\Delta p \Delta x \ = \Delta E \Delta t \ \geq \ h/(4\pi)$$

with $\nu \ = \ E/h$, and Δt the lifetime of the excited state, usually of order 10^{-8} second, we have

$$\Delta \nu \Delta t \ \geq \ 1/4\pi$$

$$\Delta \nu \ \geq \ 1/4\pi \Delta t \ = \ 8 \times 10^6 \mathrm{sec}^{-1}$$

For an optical line, say NaI D at 5890Å, $\Delta\nu/\nu \sim 1.6{\times}10^{-8}$, so observing such a line with a resolution, R, much higher than 10^8 cannot yield any information.

This is essentially a physical limit set by quantum mechanics and the reality of observing sources whose "temperatures" are not absolute zero.

• 3. Time resolution > the age of the Universe or < the size of a source × the speed-of-light (or in some cases, the size of the source times the sound speed).

For example, a black hole of solar mass is ~ 1 km in size, so the shortest time variability we are likely to be able to see from sources like that is $1/3{\times}10^5$ or $3{\times}10^{-6}$ sec or $3{\times}10^5$ Hertz . The longest timescale is (now!) $\sim 10^{18}$ sec.

• 4. Angular resolutions on scales $> 2\pi$ — e.g. the Cosmic microwave background dipole, or smaller than the diffraction limit of the observing system.

The minimum observable scale (and thus maximum angular resolution) is give by the wavelength/frequency of observation and the maximum baseline you can effect. For Earthbound baselines, this is

$$\lambda/(3 \times 10^9) \text{ Radians}$$

for the Solar System this is of order

$$\lambda/(3 \times 10^{14}) \text{ Radians}$$

• 5. Spatial resolutions smaller than the effective size of the object or phenomenon.

It's easiest to couch this limit in terms of the size of the object to be observed, so for astrophysical sources, a basic limit is

$$1 \ km/(M/M_\odot)$$

Or, for other sources like the atmospheres stars or features in the interstellar medium, no size smaller than the size of the source when the optical thickness (depth) at the wavelength/frequency of observation is greater than unity

$$\tau_\nu \text{ at } \nu \ \rightarrow > \ 1$$

This isn't true for solar system objects, for example, where we can observe either telescopically or via spacecraft features on the surface of the moon and planets at much smaller scales.

There is an additional spatial scale limit related to the observation. It is not possible to observe spatial scales smaller than the wavelength of observation.

$$\Delta l \; < \; \lambda,$$

essentially a coherence limit.

III. Other Limits

Two other observational limits come into play.

The Joint Observation Limit is that we cannot observe time variability when we approach the instrument bandwidth or spectral frequency. E.g. if you're chopping an IR detector at 10 Hz, you cannot see variability on timescales of 10 Hz or higher. This is another principle equivalent to the Uncertainty Principle.

And the Intensity Limit states that given that QE $\leq$ 1.0, one must observe with reasonable integration times. This can also be extended to a "Background" Limit, such as that first described by H. (Chip) Arp for galaxies, where objects of surface brightness sufficiently below that of the night sky are essentially undetectable (in any reasonable integration time). This is one of the reasons we go to space and are planning to put astronomical satellites (SIRTF, etc.) far from the earth. Note, too the converse of this argument, which was also described by Arp, most probably brought on by the discovery of Quasistellar sources (Quasars): if a galaxy is apparently small enough and of high enough surface brightness it will not be morphologically classified as a galaxy but rather as a star.

The combination of these connundrums for galaxy catalog builders has lead to the intensive study of low surface brightness galaxies and the question of whether our census of the nearby Universe is sufficiently biased to eliminate the need for dark matter.

Arp, H. 1965, ApJ 142, 402.

IV. Phase Space

Now that we have outlined some of the observational limits, we can look at observational phase space and how astronomers have been able to cover it as a function of time.

1. Spectral Resolution versus Wavelength. R = 1 is the "Photometry" limit.
2. Time Resolution versus Wavelength.
3. Angular Resolution versus Wavelength.
4. Polarization versus Wavelength.
5. Sensitivity versus Wavelength (and time).