NLSRT Memo No. 65

CO EMISSION AT HIGH REDSHIFT

Robert L. Brown

June 15, 1989

One of the scientific areas that the GBT represents a truly significant advance over any existing telescope is in the study of the molecular content of evolving or primeval galaxies. Briefly, the IRAS survey has provided for us a sample of extraordinarily luminous galaxies whose luminosity appears to be dust-processed ultraviolet emission which we see emitted in the far infrared. The source of the ultraviolet radiation is most likely to be a population of short-lived O and B stars. If this is correct then, given the luminosity of the IRAS galaxies, star formation is proceeding at an unsustainably high rate, $> 10^2$ solar masses per year. Hence, we are observing a transient or episodic phenomenon now known as a "starburst"; the luminous IRAS galaxies themselves are "starburst galaxies."

Star formation in the Milky Way appears to be an inefficient process whose first step is the accumulation of a large reservoir of atomic and molecular gas. Self-gravity or passing shocks trigger the formation of stars in a small fraction of the mass of the molecular gas. If such a process applies not only in the Milky Way but also in the IRAS starburst galaxies, then we would expect to find an enormously massive molecular reservoir fueling the starburst phenomenon. As you know, several groups, Sanders, Scoville and their colleagues notable among them, principally working on the 12 meter telescope, have shown this to be the case. CO(J=1-0) emission has been detected at velocities somewhat past 30,000 km s^{-1} (z=0.10) with peak antenna temperatures of 0.005 K to 0.010 K.

The molecular searches are guided by the IRAS survey which itself has a sensitivity threshold such that it is increasingly incomplete beyond z=0.1.

If we wish to follow the evolution of the molecular content of galaxies to higher redshift, we need another sample of objects. The similarity between the bolometric luminosity of IRAS starburst galaxies and quasars suggests that a fruitful investigation would involve a study of CO emission from quasar-host galaxies. Using quasars, of course, allows us to observe the most distant objects known. The redshifted CO emission from quasars at $z > 1$ will be found in the "7mm" band of the GBT while those at z approaching 4 will be discovered at K-band. But how strong can we expect the redshifted CO lines to be?

Let us begin to answer this question by assuming that the CO luminosity of a "typical" quasar is equal to, but no greater than, that of a "typical" IRAS starburst galaxy such as can be seen at $z \leq 0.1$ on the 12 meter telescope. Call this luminosity L_{CO} (ergs s^{-1}). For an object at redshift z and distance d, the observed flux is

$$F_{CO} = \frac{L_{CO}}{4\pi d^2 \ (1+z)^2} \quad ,$$

where F_{CO} has units erg s^{-1} cm^{-2}. The two factors of (1+z) in the denominator arise as follows: First, the energy of each photon is diminished by (1+z)--this is just the usual redshift factor--and, second, the rate at which photons arrive is decreased by the same factor, "time dilation" (e.g., Peebles "Physical Cosmology" Chapter VI). Stated another way, to correct L_{CO}(erg s^{-1}) from the emitted to the observed reference frame we need to correct both "erg" and "s^{-1}" for the redshift.

In a homogeneous Friedmann model we can write the distance as

$$d = \left(\frac{c}{H}\right) \left\{ \frac{qz + (q-1)[(1+2qz)^{1/2} - 1]}{q^2 \ (1+z)^2} \right\} \quad ,$$

where q and H are the deceleration parameter and Hubble's Constant, respectively. Thus,

$$F_{CO} = \frac{L_{CO}}{4\pi} \left(\frac{H}{c}\right)^2 \frac{q^4 (1+z)^2}{\{qz + (q-1) \quad [(1+2qz)^{\frac{1}{2}} - 1]\}^2} \quad .$$

F_{CO} represents the power in the line, the integral over the profile. For simplicity, assume the profile is rectangular so we can write

$$F_{CO} = f_{CO} \, \Delta\nu$$

and f_{CO} (ergs s^{-1} cm^{-2} Hz^{-1}) is the flux density at the peak of the line. Although f_{CO} is an observable, observers often prefer to work in units of antenna temperature, and here the relation for sources smaller than the beam is

$$T_A = \left(\frac{f_{CO}}{2k}\right) \eta A \quad ,$$

where eta is the telescope aperture efficiency and A is the area of the telescope.

Now we may compare T_A expected for a high redshift quasar observed by the GBT with the T_A actually observed from an IRAS galaxy on the 12 meter telescope. Recall both quasar and IRAS galaxy have the same L_{CO}. Let the subscript 1 refer to the IRAS galaxy and its observations while the subscript 2 will refer to the quasar and its observations. The ratio of CO antenna temperatures is,

$$\frac{T_2}{T_1} = \left(\frac{f_2}{f_1}\right) \left(\frac{A_2}{A_1}\right) \left(\frac{\eta_2}{\eta_1}\right)$$

$$= \left(\frac{F_2 \; A_2 \; \eta_2}{F_1 \; A_1 \; \eta_1}\right) \frac{(1 + z_2)}{(1 + z_1)}$$

or

$$\frac{T_2}{T_1} = \frac{A_2\ \eta_2}{A_1\ \eta_1} \left(\frac{1+z_2}{1+z_1}\right)\left(\frac{1+z_2}{1+z_1}\right)^2 \left\{\frac{qz_1 + (q-1)\ [(1+2qz_1)^{1/2} - 1]}{qz_2 + (q-1)\ [(1+2qz_2)^{1/2} - 1]}\right\}^2$$

Note this doesn't depend on Hubble's constant, but does depend on q. (If such a thing as a CO "standard candle" exists, can we get q from these observations?)

As an example, choose $q=1/2$, $z_1=0.10$, $z_2=3.0$, A_1 is the area of the 12 meter, and A_2 is the area of GBT. In this case

$$\frac{T_2}{T_1} = 2.2(\eta_2/\eta_1)$$

and the redshifted z=3 CO line from the QSO-host galaxy will have a greater antenna temperature on the GBT than will a galaxy at z=0.1 with identical CO luminosity detected on the 12 meter. Stated in the manner of "Scientific Considerations for The Design of a Replacement for the 300 foot Radio Telescope": Any galaxy that can presently be detected in CO on the 12 meter, if moved to high redshift, could be detected by the GBT.