CO (AND OTHER) LINES FROM THE CLOVERLEAF QUASAR

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1. Introduction

The Cloverleaf quasar (H1413+117) at redshift 2.56 derives its name from its optical image, which is gravitationally lensed into a pattern of four points with separations of about $1''$. The lensing galaxy is unseen, but models assuming an elliptical potential at intermediate redshift give total magnifications of roughly a factor of 10 (Kayser et al. 1990). The Cloverleaf's optical spectrum has classical broad emission lines, plus broad absorption troughs–it is classified as a BALQ (broad absorption line quasar).

We initially selected the Cloverleaf for molecular line studies because of its strong submillimeter emission, detected during a survey of radio quiet quasars and BALQs at the JCMT (Barvainis, Antonucci, and Coleman 1992). The Cloverleaf was also detected by IRAS and has a far-IR/submm spectrum identical to the luminous infrared galaxy IRAS F10214+4724 at $z = 2.28$ (Barvainis et al. 1995). F10214+4724 was, of course, the first high-z object to be convincingly detected in CO (Brown and Vanden Bout 1992; Solomon, Downes & Radford 1992), with the Cloverleaf being the second (Barvainis et al. 1994). Several new lines of evidence link F10214+4724 closely with the Cloverleaf: spectropolarimetry of F10214+4724 shows broad optical emission lines in reflected light, meaning that it harbors a hidden quasar (Miller 1995); F10214+4724 now appears to be gravitationally lensed (e.g., Broadhurst and Lehár 1995); and similar far-IR and CO emission, but different optical emission, in the two objects suggests that they differ primarily in orientation, with F10214+4724's nucleus obscured by a surrounding dusty torus (Barvainis et al. 1995).

Here I present new millimeter observations of line emission from the Cloverleaf. My collaborators in this work are Ski Antonucci, Danielle Alloin,

Linda Tacconi, Paul Coleman, and Phil Maloney.

2. Observations and Results

We observed the Cloverleaf using the IRAM 30 m telescope on Pico Veleta in June 1994 and May 1995. Because of the unique ability of the 30 m to collect data in the 3 mm, 2 mm, and 1 mm bands simultaneously, we were able to observe a rather large suite of lines. This has resulted in definite detections in CO $J = 3-2$, $4-3$, $5-4$, and $7-6$ (see Figure 1), and an upper limit on ^{13}CO$(3-2)$ emission. Space limitations preclude showing all the spectra here, but a very likely detection of the atomic carbon fine structure line CI($^3P_1 - ^3P_0$) was obtained, as was an upper limit on CI($^3P_2 - ^3P_1$). We also have a possible detection of HCN$(4-3)$ at the $T_A^* = 1$ mK level, which required some 7 nights of integration. Finally, we have an upper limit on CO$(1-0)$, at $\nu_{\rm obs} = 32.4$ GHz, using the Haystack 37 m telescope in January 1995. This limit is consistent with CO$(1-0)$ being no more than about a factor of two brighter than the thermalized value relative to CO$(3-2)$.

These results will be discussed in detail in a future paper (Barvainis et al. 1996). A few general statements can be made here. First, the CO excitation is interesting, in that CO$(4-3)$ appears to have a higher brightness temperature than either CO$(3-2)$ or CO$(5-4)$. This probably means that conditions are such that the critical density for the CO$(4-3)$ transition obtains, and that the lines are not too optically thick. Second, the (possible) detection of HCN means that there is probably a large quantity of high density gas ($n \sim 10^5$ cm^{-3}) present in the Cloverleaf. The HCN/CO brightness temperature ratio is 0.2, very much like the values found in luminous IRAS galaxies. Finally, the CI/CO ratio is also about 0.2, which is similar to the value in IC 342 (the only other extragalactic source where both species have been clearly measured).

3. Conclusion

Although there have been many attempts to detect high-z CO emission, only the Cloverleaf and F10214+4724 have been definitely confirmed. It appears that the boosting derived from lensing, uncertain but perhaps an order of magnitude, is essential for studying gas in the early universe, given current instrumentation. Therefore, we need to derive as much information as we can from molecular line studies of the two objects where such studies are now possible. Detailed modeling of the various lines presented here promises to provide interesting constraints on molecular gas in the Cloverleaf quasar at an epoch when the universe was only one-seventh its current age.

References

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Figure 1. Four transitions of CO in the Cloverleaf quasar. For ease of comparison, the spectra have been put on a brightness temperature scale (in Kelvins), arbitrarily assuming a source size of $0.3''(\approx 1.7$ kpc at the source).