COMPARATIVE STUDIES OF OTHER GALAXIES

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Abstract. Knowledge of the distribution and physical properties of the molecular gas content of external galaxies is crucial for understanding their dynamics and, in combination with data obtained across the electromagnetic spectrum, the role of star formation in their evolution. Due to its high abundance and line strength, CO plays a key role in these investigations. This paper will concentrate on recent results obtained during the past five years. Previous work will be briefly summarized. This article covers multi-line studies of ultraluminous infrared galaxies at cosmological distances like F10214+4724 (z=2.29) or the Cloverleaf quasar (z=2.56), nearby starburst and active galaxies such as IC 342, M82, and Centaurus A, and nearby spiral galaxies like M51.

1. Introduction

Since the first detection of ^{12}CO J=1-0 line emission in an extragalactic system 20 years ago (Rickard et al. 1975; Solomon and de Zafra 1975), CO has played a key role in the investigation of the dense molecular interstellar medium in galaxies. During recent years these studies have been extended towards redshifts as high as z=2.56 (Cloverleaf). The results of previous years have been summarized in Young and Scoville (1991) and Henkel, Baan, and Mauersberger (1991). Earlier reviews are by Morris and Rickard (1982); Soifer et al. (1987); Telesco (1988); and Cohen(1989).

The efficiency with which the molecular gas mass $M(\mathrm{H}_2)$ in galaxies is transformed into massive stars that are responsible for the far-infrared luminosity L_{IR} can be measured by the $L_{\mathrm{IR}}/M(\mathrm{H}_2)$ ratio (Young and Scoville 1991; Downes, Solomon, and Radford 1993; Sanders et al. 1988) and is reflected in a correlation between L_{IR} and $M(\mathrm{H}_2)$ that has now been extended towards luminosities in excess of $10^{12}\mathrm{L}_\odot$ (e.g. Sanders et al. 1988;

Brown and Vanden Bout 1992; Barvainis et al. 1994). The validity of this correlation out to large distances can also be taken as an argument that the FIR-luminosity is due to thermal emission rather than non-thermal synchrotron emission (Alloin et al. 1992). Multi-level isotopic line emission can be used in radiative transfer calculations to determine the physical state (density, temperature, and abundances) of the interstellar medium. ^{13}CO line emission has now been detected towards a large number of galaxies (e.g., Sage and Isbell 1991; Casoli, Dupraz, and Combes 1992) including the nearby QSO I Zw 1 (Eckart et al. 1994). Besides, the detection of high redshifted CO molecular line emission is also becoming statistically more important for cosmology (see analysis of the FCRAO survey in Verter 1991, 1992). Dickey and Kazès (1992) and Schöniger and Sofue (1994, with a sample of 32 galaxies) have shown that a Tully-Fisher relation for the CO line can be established. Although the line shapes of HI and CO are sometimes very different, CO emission evidently extends beyond the peak of the rotation curves in most spiral galaxies. Therefore, one finds a perfect relation between the linewidths in CO and HI. The linewidths are correlated with the absolute magnitude, so they can be used as a distance indicator.

2. Ultraluminous Infrared Galaxies

Progress in receiver technology and the operation of large millimeter wavelength single dish telescopes and sensitive interferometers now also allow study of the molecular gas phase in ultraluminous galaxies at cosmological distances. In these objects like the galaxy F10214+4724 at z=2.29 (P.Solomon in this edition; Brown and Vanden Bout 1992) or the Cloverleaf quasar at z=2.56 (S.Radford and R.Barvainis in this edition; Barvainis et al. 1994), the molecular gas accounts for a substantial fraction of their total dynamical mass. More detailed investigations of these objects may improve our understanding of galaxies at early stages of their evolution. F10214+4724 and the Cloverleaf are the two most luminous high redshift objects in which intense CO emission with an implied molecular hydrogen mass of about 10^{11}M$_\odot$has been discovered. Yamada et al. (1995) report the possible detection of molecular line emission from a quasar at z=2.88 which implies a molecular gas mass of $\sim 10^{12}$M$_\odot$. For F10214+4724, multi-line observations (Brown and Vanden Bout 1992; Solomon et al. 1992; Sakamoto et al. 1992; Radford, Brown, and Vanden Bout 1993) show the bulk of the molecular gas is warm and dense with $n(\mathrm{H}_2) \approx 5 \times 10^3 \mathrm{cm}^{-3}$ if $T_{\mathrm{kin}} = 50$ K. Of particular interest is the fact that the Cloverleaf is a well-known gravitational lens. The question then arises whether the implied large molecular gas masses are significantly overestimated due to amplification by the foreground lens. This may also be the case for F10214+4724.

3. Nearby Starburst and Active Galaxies

With a large number of sensitive interferometer arrays with angular resolutions of the order of $2''$, it is now possible to obtain detailed information on the distribution and dynamics of the nuclear molecular gas. Current studies indicate that the structures of nearby starburst galaxies are dominated by molecular rings and bars that in most cases can be interpreted as part of the inner spiral structure of the corresponding galaxies. These structures are in agreement with the hypothesis of infalling gas streaming along a nuclear stellar bar. As in the Seyfert 2 galaxy NGC 1068 (see also contributions by L.J.Tacconi and T.T.Helfer in this edition), these measurements give direct evidence for nuclear molecular gas concentrations and gas feeding in active nuclei as postulated in 'unified models'. Isotopic multiline studies of different molecules indicate for the nuclei rather dense and warm molecular gas with $n = 10^3 - 10^5$ cm^{-3} and $T_{\rm kin} \sim 30$ K. Well studied examples are IC 342, a gas-rich spiral showing a mild nuclear starburst, M82, the archetypical starburst galaxy, and Centaurus A (see also the contribution by W.Wild in this edition), the closest radio galaxy.

IC342: Single dish and interferometer multi-line studies (Xie, Young, and Schloerb 1994; Eckart et al. 1990a; Güsten et al. 1993; Wright et al. 1993; Wall et al. 1993; Irwin and Avery 1992; Turner and Hurt 1992) show that the properties of the $\sim 10^8$ M$_\odot$ molecular gas within the central kpc vary as a function of position. In interferometer maps the bar of molecular gas is resolved into two spiral arms that meet in a 100 pc diameter ring. The most recent, highest spatial resolution maps of IC342 (Wright et al. 1993; Turner and Hurt 1992) reveal peaks in the line emission probably corresponding to giant molecular cloud complexes (GMCs) 20-25 pc in size with molecular gas masses of $\sim 10^6$ M$_\odot$. These observations are complemented by subarcsecond imaging spectroscopy in the near-infrared, e.g., with the MPE 3D spectrometer (Böker et al. 1996). This now allows full modeling of the deeply embedded stars and molecular gas in IC342 and other galaxies.

M82: Morphology and molecular excitation has been studied extensively in this archetypical starburst galaxy. Recent multi-line and gas dynamical studies are by White et al. (1994); Brouillet and Schilke (1993); Wild et al. (1992); Sofue et al. (1992); Tilanus et al. (1991); Phillips and Mampaso (1989). Although the ^{12}CO(2–1)/^{12}CO(1–0) ratio is generally measured to have values ranging between 1.3 and 2, indicative of a contribution from warm optically thin gas, Wild et al. (1992) find that the strength of the CO J=6–5 emission in comparison with the lower-J lines, as well as the ratios of isotopic lines, indicate that the lower rotational transitions of ^{12}CO are optically thick. The bulk molecular gas temperature is $\sim$ 45 K, with $n \sim 10^4$ cm^{-3} and $^{peak}N(\mathrm{H_2}) \sim 5 \times 10^{22}$ cm^{-2} in a $13''$ beam. The centrally

peaked $C^{18}O$ J=2-1 data reveal about $10^8 M_\odot$ of molecular gas within the 400 pc diameter double lobed ring structure seen in ^{12}CO.
Cen A: SEST (Eckart et al. 1990b; Israel et al. 1990; Rydbeck et al. 1993) and CSO (Quillen et al. 1992; Phillips et al. 1987) observations of Centaurus A show that, similar to the ionized gas as seen in Hα, $2\times10^8 M_\odot$ of molecular gas are distributed in a thin warped disk in a prolate potential. In addition to this, Israel et al. (1990) as well as Rydbeck et al. (1993) find evidence for an edge-on circumnuclear ring with a radius of $\sim$100 pc and rotational velocities of 220 km/s^{-1}. This ring is perpendicular to the radio jet and implies an enclosed mass of 1.4×10^9 $M_\odot$.

4. Nearby Spiral Galaxies

Due to their proximity, nearby spirals can be studied with the highest spatial resolution. Individual GMCs and the distribution and dynamics of the molecular gas in the disks can be investigated. Detailed knowledge of the physical properties of these systems represents an important reference point to which extreme properties of ultraluminous and more distant active galaxies have to be compared. M31 and M33 are covered in the contribution by P. Thaddeus in this edition (see also the review article by Young and Scoville 1991). For M51, single dish and interferometer maps (Guélin et al. 1989; Rand 1993; Adler et al. 1992; Garcia-Burillo, Combes, and Gerin 1993; Garcia-Burillo, Guélin, and Cernicharo 1993) now account for all the line flux and consistently find wider spiral arms (about 1.3 kpc or less) than seen previously (Vogel et al. 1988, Rand and Kulkarni 1990). The average integrated intensity arm-to-interarm contrast is of the order of 5:1 with peak values 4 times higher in the inner arms. A detailed picture of the velocity field in M51 shows streaming motions along the arms and turbulent motion close to the center (Garcia-Burillo, Guélin, and Cernicharo 1993). The structure of the CO, HI, and Hα line emission across the arms reflects the influence of a density wave system and the variation of massive star formation (Knapen et al. 1992; Adler et al. 1992). 3D Monte-Carlo simulations (Garcia-Burillo, Combes, and Gerin 1993) indicate that the dynamics as well as the arm-to-interarm contrast can probably be understood as a consequence of an encounter with NGC 5195.

5. Molecular Excitation

Under LTE conditions we expect $^{12}CO(2\text{-}1)/^{12}CO(1\text{-}0)$ line temperature ratios near 1.0 for dense (the critical density to populate the J=2 level is 2×10^4 cm^3), warm (T>20 K), and optically thick gas, and 4 for dense, warm, and optically thin gas. A ratio <1 can indicate low temperatures for optically thick lines. Deviations from the LTE values can also occur when the density is too low to thermally populate the rotational levels, as in many envelopes of clouds in our Galaxy. Several surveys to probe the molecular excitation in nuclei of galaxies have recently been compiled (e.g., Braine and Combes 1992, 1993; Wall et al. 1993; Sage and Isbell 1991; see also the contributions of S. Aalto-Bergman and T. Hasegawa in this edition). They find the ^{12}CO(2-1)/^{12}CO(1-0) line ratio is of the order of 0.9 and indicates molecular line emission from dense warm molecular gas. Bright ^{12}CO line emission from nuclei of nearby galaxies (NGC 253, IC 342, M 82, NGC1068, and NGC 6946) in the submillimeter J=6-5 (Harris et al. 1991) and J=4-3 (Güsten et al. 1993) transition convincingly demonstrates the presence of dense warm molecular material in the nuclei of galaxies with star formation activity. In nearby galaxies where the disk component can be resolved or in distant objects where the beam filling is dominated by the disk, the ^{12}CO(2-1)/^{12}CO(1-0) ratio is of the order of 0.5 indicative of cold and/or subthermally excited molecular gas (e.g., for M31, Allen and Lequeux 1994).

The molecular gas is probably excited by a combination of mechanisms. The gas in dense molecular clouds may be excited by an enhanced cosmic ray ionization rate (e.g., Goldsmith & Langer 1978; de Jong et al., 1980) that may be two orders of magnitude above the standard Galactic value of a few times 10^{-17} s^{-1} in M82 (Schilke et al. 1993). Such an enhancement might be due to the high star formation activity and can probably be measured directly, if the non-thermal radio flux density is proportional to the cosmic ray density. A further efficient heating mechanism is the intense UV radiation field expected from an increased number of OB stars in a starburst or in embedded active nuclei. Photoelectric heating and far-UV pumping of H_2 will heat surfaces of molecular clouds up to a few hundred degrees (Tielens & Hollenbach 1985; Sternberg and Dalgarno 1989). This may result in strong far-infrared cooling lines (Crawford et al. 1985) and optically thin emission from hot CO on the photodissociated cloud surfaces. For the nuclei of galaxies, turbulent heating can also be important, as is probably the case in the Galactic Center (Zhao, Goss, and Ho 1995).

6. Absorption Spectroscopic Studies

Absorption studies against bright nonthermal nuclear continuum sources are of great value since they provide a "pencil beam" measurement of the characteristics of the molecular clouds responsible for the absorption features and give a deeper insight into the properties of the interstellar medium of the corresponding galaxies. Up to now there are only two sources for which millimeter absorption spectroscopic studies have been published: Centaurus A (Phillips et al. 1987; Israel et al. 1990; Eckart et al. 1990c) and the BL Lac object PKS 1413+135 $z = 0.2467$ (Wiklind and Combes 1994). Barvainis and Antonucci (1994) searched for CO absorption towards Cygnus A without success. This may either indicate the absence of a molecular torus or may be explained by extraordinarily large rotation temperatures due to the presence of the strong nonthermal nucleus (Maloney et al. 1994). For Centaurus A, absorption lines of ^{12}CO, ^{13}CO, HCO^+, HCN, CN, and CS (Eckart et al. 1990c; Israel et al. 1990) show a number of features with line widths of a few km s^{-1}. They can be attributed to individual molecular clouds with properties similar to dense molecular clouds in our Galaxy. CO absorption line ratios, as well as the hyperfine line ratios for CN and HCN, indicate the deepest absorption at the systemic velocity of Centaurus A originates in quiescent molecular clouds that are cold, dense, and clumped and happen to lie along the line of sight to the central compact continuum source.

7. Open Questions

In the future, multi-line studies of ultra luminous galaxies at high redshift are required in order to determine the mass and physical properties of their molecular gas. Since the molecular mass apparently constitutes a large fraction of the dynamical mass, such a study is essential to understanding galaxy evolution and the transformation of gas into stars. A search for systems where the molecular lines can be studied in absorption is required. If the molecular gas plays a dominant role in the interstellar media of galaxies at cosmological redshifts, one should expect more absorption line systems in quasars. Important open questions are: Do the differences in infrared luminosity and CO line emission reflect an evolutionary sequence? Is there a valid unified model that links the different source classes? What are ultraluminous objects? Are they powered by a central star burst or a hidden QSO or both? Detailed multi-frequency high spatial resolution investigations of samples of galaxies are required to tackle these questions.

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References

Adler, D.S., Lo, K.Y., Melvyn, C.H., Wright, C.H., Rydbeck, G., Plante, R.L., Allen, R.J., 1992, Ap. J., 392, 497.

Allen, R.J., Lequeux, J., 1994, p.105, in Proc. of a Conference on "Nuclei of Normal Galaxies: Lessons from the Galactic Center" held at Schloß Ringberg (Tegernsee), July 26-30, 1993, (eds.) R.Genzel & A.I.Harris, Kluwer (Dordrecht).

Alloin, D., Barvainis, R., Gordon, M.A., Antonucci, R.R.J., 1992, Astron. Astrophys., 265, 429.

Barvainis, R., Antonucci, R., 1994, A. J., 107, 1291.
Barvainis, R., Tacconi, L., Antonucci, R., Alloin, D., Coleman, P., 1994, Nature, 371, 586.
Böker, T., et al. 1996 in preparation
Braine, J., Combes, F., 1992, Astron. Astrophys., 264, 433.
Braine, J., Combes, F., 1993, Astron. Astrophys., 269, 7.
Brown, R.L., Vanden Bout, P.A., 1992, Ap. J., 397, L19.
Brouillet, N., Schilke, P., 1993, Astron. Astrophys., 277, 381.
Casoli, F., Dupraz, C., Combes, F., 1992, Astron. Astrophys., 264, 55.
Cohen, R.J., 1989, Rep.Prog.Phys, 25,881
Dickey, J.M., Kazès, I, 1992, Ap. J., 393, 530.
Downes, D., Solomon, P.M., Radford, S.J.E., 1993, Ap. J., 414, L13.
Crawford, M.K., Genzel, R., Townes, C.H., and Watson, D.M., 1985, Ap. J., 291, 755.
Eckart, A., Downes, D., Genzel, R., Harris, A.I., Jaffe, D.T. and Wild, W., 1990a, Ap. J., 348, 434.
Eckart, A., Cameron, M., Wild, W., Zinnecker, H., Rydbeck, G., Olberg, M., Wiklind, T., 1990b, Ap. J., 363, 451.
Eckart, A., Cameron, M., Genzel, R., Jackson, J.M., Rothermel, H., Stutzki, J., Rydbeck, G., Wiklind, T., 1990c, Ap. J., 365, 522.
Eckart, A., van der Werf, P.P., Hofmann, R., Harris, A.I., , 1994, Ap. J., 424, 627.
Garcia-Burillo, S., Combes, F., Gerin, M., 1993, Ap. J., 274, 148.
Garcia-Burillo, S., Guélin, M., Cernicharo, J., 1993, Astron. Astrophys., 274, 123.
Goldsmith, P.F. and Langer, W.D., 1978, Astron. Astrophys., 222, 881.
Güsten, R., Serabyn, E., Kasemann, C., Schinckel, A., Schneider, G., Schulz, A., Young, K., 1993, Ap. J., 402, 537.
Guélin, M., Garcia-Burillo, S., Blundell, R., Cernicharo, J., Despois, D., Steppe, H., 1989, Highlighs Astron. Vol.8, p.575
Harris, A.I., Hills, R.E., Stutzki, J., Graaf, U.U., Russell, A.P.G., Genzel, R., 1991, Ap. J., 382, L75.
Henkel, C., Baan, W.A., Mauersberger, R., 1991, Astron. Astrophys. Review, 3, 47.
Irwin, J.A., Avery, L.W., 1992, Ap. J., 388, 328.
Israel, F.P., van Dishoeck, E.F., Baas, F., Koornneef, J., Black, J.H., de Graauw, Th. 1990, Astron. Astrophys., 227, 342.
de Jong, T., Dalgarno, A. and Boland, W., 1980, Astron. Astrophys., 91, 68.
Knapen, J.H., Beckman, J.E., Cepa, J., van der Hulst, T., Rand, R.J., 1992, Ap. J. (Letters), 385, L37.
Malony, P.R., Begelman, M.C., Rees, M.J., 1994, Ap. J., 432, 606.
Morris, M., Rickard, L.J., 1982, Annu.Rev.Astron.Astrophys., 20, 517.
Phillips, T.G., Ellison, B.N., Keene, J.B., Leigthon, R.B., Howard, R.J., Masson, C.R., Sanders, D.B., Veidt, B. and Young, K., 1987, Ap. J., 322, L73.
Phillips, J.P., Mampaso, A., 1989, Astron. Astrophys., 218, 24.
Quillen, A.C., de Zeeuw, P.T., Phinney, E.S., Phillips, T.G., 1992, Ap. J., 391, 121.
Radford, S.J.E., Solomon, P.M., Downes, D., 1991, Ap. J., 368, L15.
Rand, R.J., 1993, Ap. J., 404, 593.
Rand, R.J., Kulkarni, S.R., 1990, Ap. J., 349, L43.
Rickard, L.J., Palmer, P., Morris, M., Zuckermann, B., Turner, B.E., 1975, Ap. J., 199, L75.

Rydbeck, G., Wiklind, T., Cameron, M., Wild, W., Eckart, A., Genzel, R., Rothermel, H., 1993, Astron. Astrophys., 270, L13.
Sage, L.J., 1993, Astron. Astrophys., 272, 123.
Sage, L.J., Isbell, D.W., 1991, Astron. Astrophys., 247, 320.
Sakamoto K., Ishizuki, S., Kawabe, R., Ishiguro, M., 1992, Ap. J., 397, L27.
Sanders, D.B., Soifer, B.T., Elias, J.H., Madore, B.F., Matthews, K., Neugebauer, G., and Scoville, N., 1988, Ap. J., 325, 74.
Schöniger, F., Sofue, Y., 1994, Astron. Astrophys., 283, 21.
Schilke, P., Carlstrom, J.E., Keene, J., Phillips, T.G., 1993, Ap. J., 417, L70.
Sofue, Y., Reuter, H.-P., Krause, M., Wielebinski, R., Nakai, N., 1992 , Ap. J., 395, 126.
Soifer, B.T., Houk, J.R., Neugebauer, G., 1987, Annu.Rev.Astron.Astrophys., 25, 187.
Solomon, P.M., Downes, D., Radford, S.J.E., 1992, Ap. J., 387, L55.
Solomon, P.M., Downes, D., Radford, S.J.E., 1992, Ap. J., 398, L29.
Solomon, P.M., de Zafra, 1975, Ap. J., 199, L79.
Sternberg, A., Dalgarno, A., 1989, Ap. J., 338, 197.
Tacconi, L.J., Genzel, R., Blietz, M., Cameron, M., Harris, A.I., Madden, S., 1994, Ap. J. (Letters), 426, L77.
Telescon C.M., 1987, Annu.Rev.Astron.Astrophys., 26, 343.
Tielens, A.G.G.M., Hollenbach, D., 1985, Ap. J., 291, 722..
Turner, J.L., Hurt, R.L., 1992, Ap. J., 384, 72.
Verter, F., 1991, Ap. J., 375, 95.
Verter, F., 1992, Ap. J., 386, 398.
Vogel, S., Kulkarni, S., Scoville, N., 1988, Nature 334, 402
Wall, W.F., Jaffe, D.T., Bash, F.N., Israel, F.P., Maloney, P.R., Baas, F., 1993, Ap. J., 414, 98.
Wild, W., Harris, A.I., Eckart, A., Genzel, R., Graf, U.U., Jackson, J.M., Russell, A.P.G., Stutzki, J., 1990, Astron. Astrophys., 265, 447.
Wiklind, T., Combes, F., 1994, Astron. Astrophys., 286, L9.
White, G.J., Ellison, B., Claude, S., Dent, W.R.F., Matheson, D.N., 1994, Astron. Astrophys., 284, L23.
Wright, M.C.H., Ishizuki, S., Turnuer, J.L., Ho, P.T.P., Lo, K.Y., 1993, Ap. J., 406, 470.
Xie, S., Young, J., Schloerb, F.P., 1994, Ap. J., 421, 434.
Yamada, T., Aoki, K., Tomita, A., Takata, T., Ohta, K., Yoshida, M., 1995, Ap. J., 438, L5.
Young, J.S., Scoville, N.Z., 1991, Annu.Rev.Astron.Astrophys., 29, 581.
Zhao, J.-H., Goss, W.M., Ho, P.T.P., 1995, Ap. J., 450, 122.