CO Observations in Galactic Clouds

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During the last few years optical astronomers have been surprised to find radio astronomers using the larger optical telescopes with equipment that they have brought with them. The objects studied are usually molecular clouds and are observed using radio frequency transitions of carbon monoxide. In this article, Dr. A. R. Gillespie from the Max Planck Institute for Radio Astronomy in Bonn gives an outline of the astronomy that is produced as well as some of the results that have come from optical telescopes used in this way.

Introduction

Millimetre-wavelength spectral line astronomy is now one of the major areas of radio astronomy and tells us about the molecular clouds in the interstellar medium. Carbon monoxide (CO)* is one of the most important molecules studied, for reasons given below, and was first detected in the Orion nebula by Wilson et al. in 1970 (*Astrophys. J.*, **161**, L43) at a wavelength of 2.6 mm. Observations of CO, as with all radio-frequency transitions, are made with coherent detectors (heterodyne receivers) rather than the incoherent detectors used in optical and traditional infrared work and the telescope operates with a diffraction-limited beam. Since the radiation must be coherent at the telescope's focus the reflector's surface must be accurate to a small fraction of a wavelength. In the northern hemisphere a few radio telescopes are of sufficiently high quality and these have been used for extensive observations of CO during the last 10 years. Optical telescopes obviously have mirrors that are accurate enough for this work but, because their diameters are much smaller, they have larger beamwidths. In the south, however, only large optical telescopes are available for this work and both the ESO 3.6 m and the Anglo Australian Telescope have been used. The former by groups from the ESTEC division of the European Space Agency and the Max-Planck-Institut für Radioastronomie; the latter was used by a group from Queen Mary College, London. A 4 m radio telescope operated by CSIRO in Sidney, Australia, is now being commissioned and is beginning to produce data, but not yet at the frequencies of the CO lines.

This article will concentrate on the physics that the CO observations tell us and give examples of southern objects as these are probably of most interest to ESO users.

CO in the Interstellar Medium

CO shows the strongest observed line intensity for any molecule except the maser lines (H_2O, OH and SiO). The relevant transitions are those between the lower rotational levels of the molecule and these have frequencies of 115 GHz (J = 1-0), 230 GHz (J = 2-1) and 345 GHz (J = 3-2), etc. corresponding to wavelengths of 2.6, 1.3 and 0.9 mm for CO. The lifetime of the J = 1 level is about 10^7 secs which is much larger than for any other molecule and so with a relatively low excitation rate a large fraction of the molecules will be in this level. The long lifetime does mean that the strong line intensities observed are due to high CO abundances. The high thermal dissociation energy of 10 eV also ensures that the CO itself will be widespread, provided it is shielded from short wavelength radiation and this makes it a tracer of the interstellar medium that compares in importance with the HI observed by its 21 cm line. The necessity for at least a minimal shielding means that the CO emission will be stronger in regions of increased density where the HI is converted into molecular hydrogen and so complementary regions are observed using the two species.

As with all spectral line work, the data are obtained in the form of line shapes and intensities such as the spectrum shown in Fig. 1, usually for several positions in a source; the gas temperature and density in the emitting region must then be calculated from these. The intensity of the line is measured as degrees K of antenna temperature, a unit which comes from low-frequency radio astronomy and refers to the temperature of a source completely filling the telescope's beam. This intensity must then be corrected for atmospheric absorbtion, telescope efficiency and differences between the Rayleigh-Jeans approximation and Planck's law to give the brightness tempera-

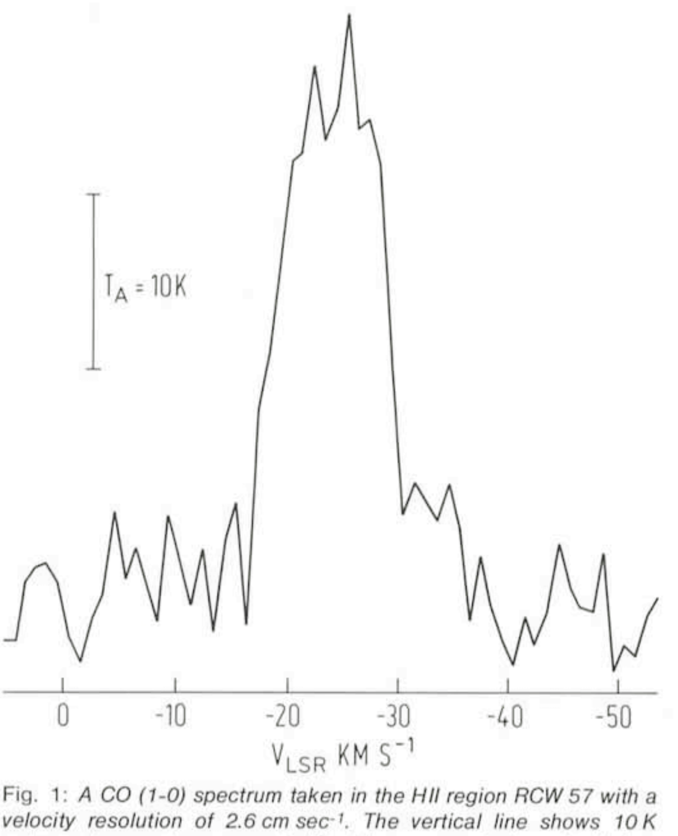

Fig. 1: *A CO (1-0) spectrum taken in the HII region RCW 57 with a velocity resolution of 2.6 cm sec⁻¹. The vertical line shows 10 K antenna temperature, corrected for telescope and atmospheric losses. A CO (2-1) spectrum taken at the same position gives a similar intensity and linewidth.*

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* In this article, a widely used convention will be adopted. This is to use CO to refer to the main isotopic form of the molecule, i. e. $^{12}C^{16}O$. Superscripts are then only used to refer to molecules containing other isotopes, e. g. ^{13}CO and $C^{18}O$.

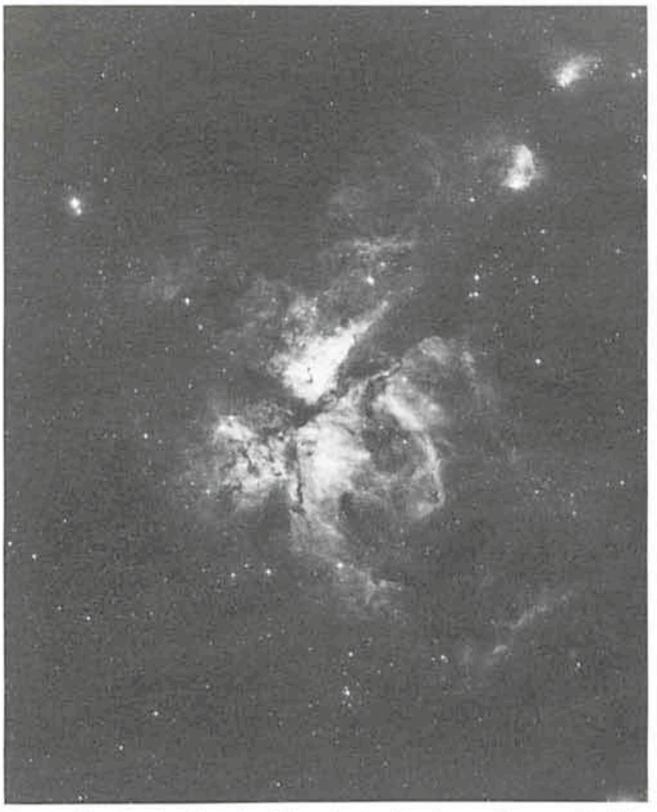

Fig. 2: *The Carina Nebula. CO emission is observed on most of the northern part of this photograph.*

ture (T_B) of the source. If the line is optically thick, and the source intensity is uniform across the telescope beamwidth, T_B is the kinetic temperature of the gas. CO is usually optically thick and gives kinetic temperatures in the range 5° for dark clouds to 70° for molecular clouds associated with HII regions. Since CO is mainly excited by collisions with H_2 molecules these temperatures then refer to the kinetic temperature of the H_2 which is the dominant component of the molecular clouds.

Unfortunately the CO's optical depth is so high that the observed lines are saturated and the CO or H_2 density cannot be calculated directly from these profiles. The density of the H_2 comes from observations of the lines due to the ^{13}CO and $C^{18}O$ isotopic variants which are optically thin and occur at frequencies relatively close to those of CO. The ^{13}CO is probably at the same excitation temperature as the CO and its optical depth can be calculated and then, taking a suitable value for the ratio $^{12}C/^{13}C$, the optical depth and density of the CO can be obtained. From this, the H_2 density can be calculated for particular models, the exact density obtained being dependent on assumptions about local thermodynamic equilibrium, radiation trapping, etc. A crude method of obtaining a mass estimate is to apply the Virial Theorem to the $^{12}C^{16}O$ line widths and neglect systematic internal notions. Clearly the CO data alone are not sufficient and usually the data are combined with those from other molecular lines and parts of the spectrum for a more detailed analysis.

Molecular Clouds

CO is so widespread that surveys have been made along the Galactic plane, showing weak emission with a similar distribution to the HII regions, but we shall restrict attention to particular molecular clouds rather than discuss the large-scale distribution of CO in our Galaxy and observations in external galaxies.

The molecular cloud associated with the Orion nebula region is one of the most extensively studied regions in the sky. CO observations have shown that there is a hot dense region associated with the Kleinmann-Low Nebula in the form of a ridge about 4′ by 9′ with a peak T_A^* of 70 K and a line width of 6 km sec^{-1}. Spectra taken at the centre of this ridge show a wider line width of 40 km s^{-1}, the plateau feature, from CO which may be optically thin and is due to very small turbulent clouds confined to an area less than 30 arc seconds diameter. There is, however, weaker CO emission extending over an area about 9° by 2° (63 pc by 14 pc) and comes from a giant molecular cloud located behind the optical nebula. The nebula is then due to recent star formation near the edge of the cloud (see, for example, Kutner et al. (*Astrophys. J.*, **215**, 521)). The spatial resolution of most observations is of the order of 1 arc minute and it is difficult to make maps of such large areas with complete angular sampling. When a smaller area is fully mapped, considerable structure is found (e.g. Gillespie and White, *Astron. Astrophys.* in press) and this can be interpreted as due to other sites of star formation or the effects of ionization/shock fronts moving through the cloud.

The Carina nebula shown in Fig. 2 is one of the brightest visible HII regions and is only accessible for observations from southern telescopes. The limited amount of CO data available shows that the CO covers an area at least 50 × 25 pc and is mainly related to the dust in the northern part of the nebula, although there is a hot-spot at the position of a radio continuum source associated with one of the regions of ionized gas. This area offers the possibility of detailed studies of the interaction of CO with dust and ionized gas when suitable facilities are available in the south.

One of the largest CO clouds in the southern sky is associated with the radio source complex G333.3 − 0.4. There are about seven radio peaks in an area 70′ by 15′, six of which lie in a line parallel with the Galactic plane. CO emission covers the whole area and the gas has considerable spatial structure and systematic velocity variations (see Fig. 3). The velocity of the CO puts the source at a distance of 4.2 kpc, well behind a visible region of HII emission (RCW 106) near G332.8 − 0.6, and the molecular cloud is about 100 pc by 35 pc. The radio and infrared data suggest that this cloud has several well developed HII regions in it.

In addition to the CO associated with the giant molecular clouds there are smaller dark regions of emission near HII regions such as that near RCW 38 shown in Fig. 4 and very small ones in dark clouds. Northern dark clouds from the Lynds catalogue have been studied by Dickman (1975, *Astrophys. J.*, **202**, 50) and a smaller globule by Martin and Barrett (1978, *Astrophys. J. Suppl.*, **36**, 1). CO emission was detected wherever dust was observed, even a small amount of dust being sufficient to protect the CO against photodissociation, and gave a kinetic temperature of 10 K for all positions in most of the clouds, and a total gas density of 10^4 cm^{-3}. The line widths and shapes of the profiles show that the clouds are gravitationally bound, but with internal motions, usually due to gravitational collapse and sometimes cloud rotation. In the southern sky the Coalsack is the most well known dark cloud complex and one of the globules in it has been ob-

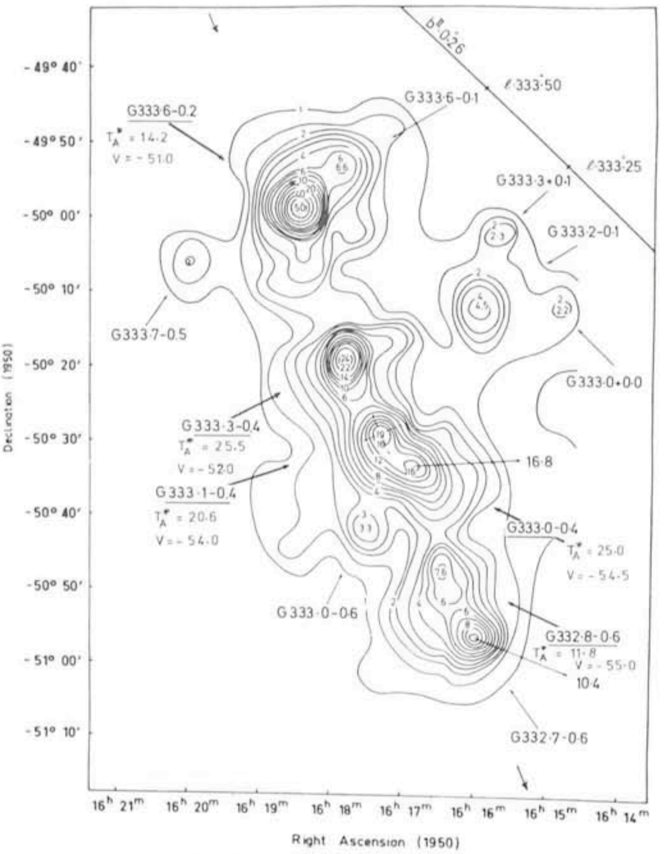

Fig. 3(a): *A radio continuum map of the G331.1 – 0.4 region with CO information added (taken from Gillespie et al 1977,* Astron. & Astrophys., **60**, *221).*

served and was found to be a typical example, with a mass of a few solar masses and a size of about 0.6 pc.

Future Observations

The above discussions have not elaborated on observations of several transitions of carbon monoxide which are now possible and becoming very important. All the CO observations made at La Silla, for example, were of

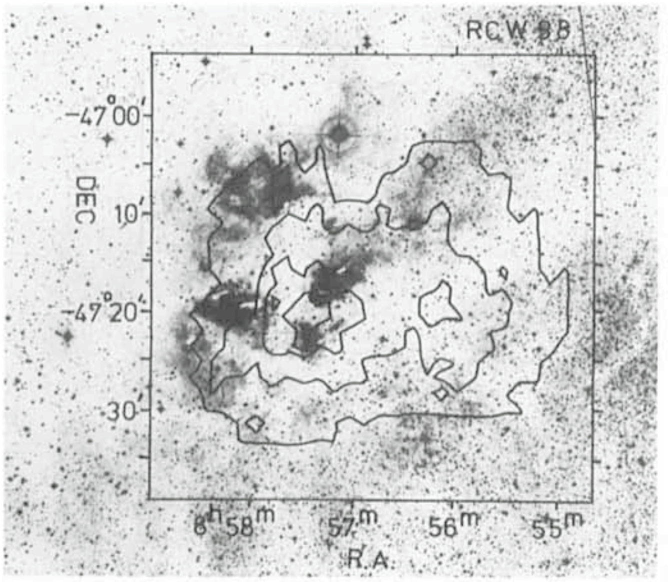

Fig. 4: *Contour map of the CO apparent brightness temperature around RCW 38 superimposed on a UKST red photograph. The lowest contour is a 3 K and the contour interval is 3 K whilst the noise level is 1 to 1.5 K. (From* Mon. Not. R. Astr. Soc. 1979, **186**, *383.)*

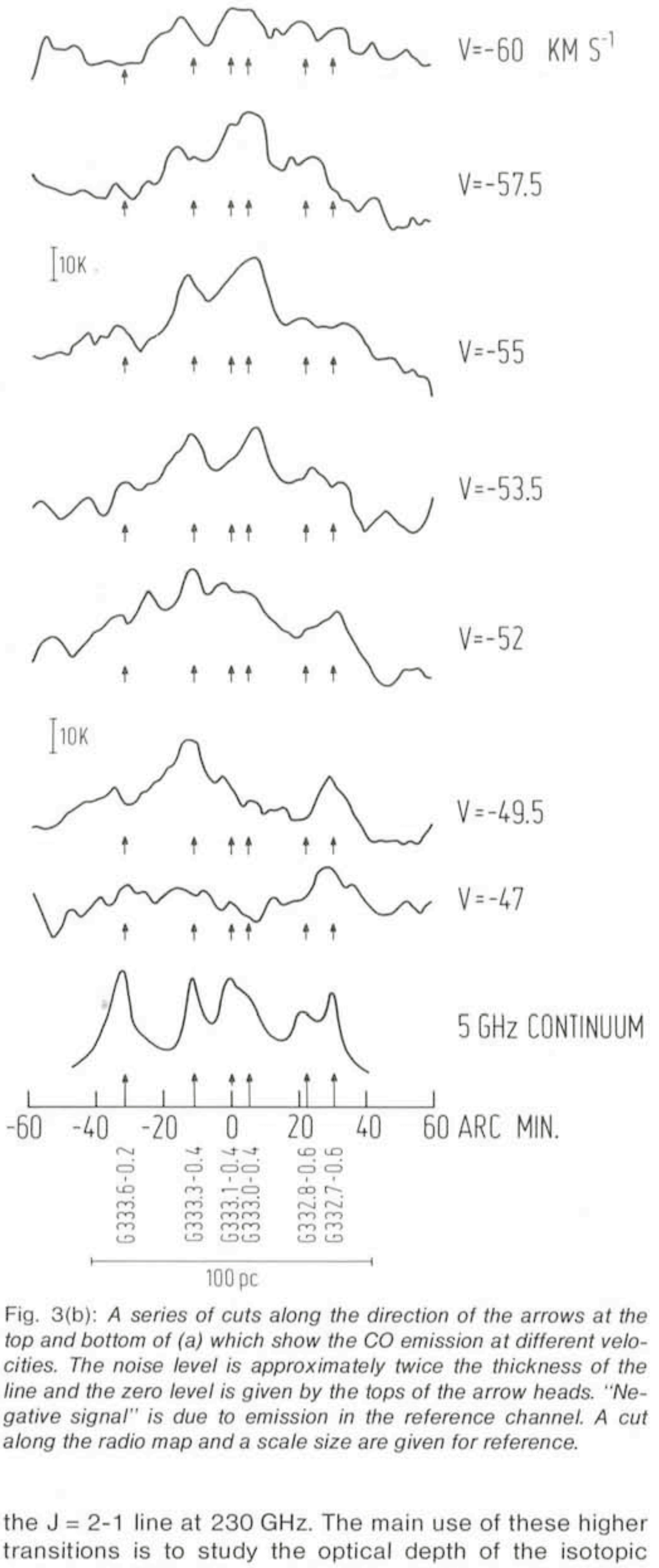

Fig. 3(b): *A series of cuts along the direction of the arrows at the top and bottom of (a) which show the CO emission at different velocities. The noise level is approximately twice the thickness of the line and the zero level is given by the tops of the arrow heads. "Negative signal" is due to emission in the reference channel. A cut along the radio map and a scale size are given for reference.*

the J = 2-1 line at 230 GHz. The main use of these higher transitions is to study the optical depth of the isotopic variants of CO and hence obtain more accurate values for the density of the molecular hydrogen and the masses of the molecular clouds. At the moment only a few northern radio telescopes are suitable for observations of the J = 2-1 transitions and one for the J = 3-2 transitions, which means that radio astronomers will be using optical and infrared telescopes for these observations until suitable radio telescopes are built. Because of this and an increasing awareness of the southern sky, radio astronomers are beginning to find themselves in the position of taking portable receivers to suitable telescopes in order to work in this rapidly expanding and exciting field.