Molecular cloud complexes in detail: Interferometric observations of GMCs in M 31

N. Neininger
(in collaboration with M. Guélin, R. Lucas and S. Muller, IRAM Grenoble)

Radioastronomisches Institut der Universität Bonn,
Auf dem Hügel 71, 53121 Bonn, Germany

Abstract. We have accumulated \(^{12}\)CO(1-0) and (2-1) data of several GMCs in M 31 using the Plateau de Bure Interferometer. The sample covers a range of 5 to 18 kpc galactocentric distance and various physical conditions. The spatial resolution attains values down to 3 pc. All GMCs investigated have been resolved into several components, also seemingly quiescent clouds and not only the cases where already the survey positions show obvious multiple-peaked spectra. Such kinematically disjunct emission is however spatially coincident in the small volume of the interferometer beam in M 31, which strongly favours local effects as the cause of the velocity splitting. This is well consistent with the observed absence of strong streaming motions in the survey data. The nature of the sometimes strong separation in velocity space needs further investigation. The complete data set (i.e. including the large-scale survey) yields a uniquely complete view of the molecular gas which allows to investigate the conditions for star formation in detail and helps to establish guide lines for the derivation of the properties of molecular gas.

1 The Framework

We have started a complete high-resolution survey of the \(^{12}\)CO in M 31 in 1995 in order to investigate the large- and small-scale properties of the molecular gas with the highest possible angular resolution and sensitivity (see the contribution of M. Guélin, this volume). One aim of this survey is to pinpoint the giant molecular cloud complexes (GMCs) in this close-by spiral galaxy for follow-up observations. Such a precise large-scale map is mandatory as a basis for further investigation because the arm-interarm contrast of the molecular gas has shown to be very high with a rather low general “filling factor” of the projected disk. The information from the survey now allows e.g. to select pointings for weaker tracers or to choose regions that merit detailed investigations with high angular resolution with the Plateau de Bure interferometer (PdBI).

M 31 is a quiescent galaxy with a low star forming rate, showing well-defined spiral arm segments; however, they resisted up to now against being put into a single global pattern. The high inclination makes a kinematical analysis on the basis of the HI data difficult (see e.g. Braun 1991), but rather large streaming motions had been derived in the north-eastern part from CO observations (Ryden & Stark 1986). The mapped areas of all such earlier work were however generally by far too small to derive general properties of the molecular gas. Our survey data now clearly show that the magnitude of non-circular motions is only of the order of 10 km s\(^{-1}\) which is the typical line width of the observed molecular gas. The total range we observed is from about 4 km s\(^{-1}\) to something like 15 km s\(^{-1}\) for individual spectra. However, we found strong small-scale disturbances at many places.

Typical examples are double- or multiple-component spectra, broad lines and short-range spatial variations (cf. Fig. 1). Unlike similar observations in the Milky Way, the location of the molecular clouds with respect to other constituents of the ISM can be determined to a much higher precision – in particular, the distance ambiguities in the interpretation are virtually absent in the M 31 CO data. Therefrom we are led to conclude that we are not observing chance line-of-sight coincidences of
spatially separated clouds, but true local effects. The sizes of such regions are of the order of a few primary beams of the PdBI, hence ideally suited for a detailed observation.

2 The sample

During the observations for the survey a large number of interesting regions showed up throughout the disk of M 31. For more detailed investigations some of them were subsequently covered at a denser sampling in both, the $^{12}$CO(1-0) and (2-1) transitions, with typical map sizes of a few ten arcminutes squared. For the PdBI observations, we choose GMCs or GMC groups that can be covered with a not too large mosaic while representing a broad spectrum of the cloud complexes found. The innermost cloud in the sample is located at a radius of $\sim$ 5 kpc, the outermost group at $\sim$ 18 kpc – this spans the whole range over which we detected CO emission in the survey. In addition, we choose other GMCs with various morphologies in different environments.

Up to now, our sample consists of six regions covered with 2- to 9-field mosaics – mainly in the south-western part of the galaxy, but also covering the prominent association of molecular gas on the northern major axis at a distance of 5 kpc from the centre.

3 A remarkable pair

Among the first objects studied in this way were two neighbouring complexes in the main “ring” of emission, separated by less than a kpc (at the location of the dust clouds D47 and D84; see Hodge 1981). One of them shows a relatively strong ($\sim$ 1 K, $\Delta v \sim$ 22 km s$^{-1}$), single peak in the survey (D84), the other two narrow peaks separated by $\sim$ 20 km s$^{-1}$ (D47) – see Fig. 1. They have not only the same distance to the centre, they lie even within the same continuous ridge of emission. Nevertheless, there must be a substantial difference in the local conditions. The H$\alpha$ map (Brinks \& Shane 1984) shows many places with such multiple spectra, but in view of the thickness of the atomic gas disk, the inclination of M 31 and possible distortions (Braun 1991) they can be explained as multiple arms in the same line of sight (Berkhuijsen et al. 1993).

This explanation is not applicable here, however: the disk of molecular gas is much thinner than the H$\alpha$ disk and the observed large-scale structure clearly excludes the existence of multiple arms within one line of sight. The same holds for the spectra in the D39 region (which are also multiple-peaked or unusually broad) since it is located close to the major axis. Fortunately, a wealth of complementary data exists for M 31 which allows to look for possible influences. In particular, we produced an overlay with the H$\alpha$ map from Devereux et al. (1994) and compared the positions with other signs of activity such as stellar associations.
Fig. 2. The CO emission of D47 and D84 compared with the Hα emission (darker tones mark higher intensities; from Devereux et al. 1994). Three representative channels each are shown as contours (solid: low, dotted: intermediate and dashed: high velocity) as in Fig. 2 of Neininger (1999). The primary-beam correction of the mosaic enhances the noise along its border. The molecular gas of D47 is concentrated in disjunct filaments, whereas D84 consists of kinematically coherent clumps. Obviously, D84 is located in a quiescent environment, whereas the GMC in D47 lies on the border of a strong Hii region. This bubble (#281 in Pellet et al. 1978) is one of the brightest Hii regions in M 31.

For these three cases we can deduce an easy explanation: the presence of multiple-peaked spectra corresponds to enhanced star formation activity in the vicinity of the GMC (cf. Fig. 2). The region of D39 is known to host several OB associations and is adjacent to one of the biggest Hii holes of M 31 (Brinks & Bajaja 1986, #8). Close to D47 we find the bubble-shaped Hii region 281 (Pellet et al. 1978) which is one of the ten brightest in M 31 and the brightest of this morphology. The CO ridge tends to avoid the bubble, but the filaments visible in Fig. 2 are located right at the border of the ionized gas. D84, on the other hand, is rather far from any sign of activity – neither strong Hα nor large Hii bubbles are found here. This leads to the suggestion that such local energy sources are responsible for line splittings or multiple components in the CO emission. The nature of the interaction needs however further investigation, as well as the role of the individual constituents (stars, ionized, neutral and molecular gas).

4 GMCs in detail

To further investigate the structure of the GMCs, we obtained data of an inner cloud complex (in the D153 dust cloud, galactocentric radius ~ 5 kpc) at the highest possible angular resolution. We used the “A”-configuration of the PdBI which allows sub-arcsecond resolution in the CO(2-1) transition. At the distance of M 31, this corresponds to about 4 pc in linear scale.

Although the survey data show an almost structure-less blob at this position, it is clear from Fig. 3 that there is significant substructure in this complex. What looks like a well-defined entity in the survey at 23” resolution (~ 90 pc) is resolved into at least four individual clumps at the higher angular resolution. In this case, the basic elements seem to be clumps (similar to D84) rather than filaments as seen in D47. It has to be checked, however, whether this is a true distinction depending on the activity of the particular region or an effect of the lower resolution of the D47 and D84 data.

A comparison between the data at different resolutions allows us to check mass determinations on the basis of the virial theorem. Some calculations on the basis of the low-resolution data turned out to be wrong by more than a factor of ten. In the D39 region, this virial mass is up to a factor of 100 higher than the mass derived from high-resolution data or the optically thin mm dust emission. Hence, a systematic study of the GMC properties at various resolutions and comparing different approaches is essential to obtain better guidelines for the derivation of such fundamental values.

5 (Preliminary) conclusions

A statistical analysis of the GMCs in the survey as well as a more detailed investigation of the properties of the clumps in the PdBI data is under way. Already the few rather compact cloud complexes investigated thus far hint however at important implications for the properties of molecular...
PdBI observations of GMCs in M 31

Fig. 3. Channel maps of the $^{12}$CO(2-1) emission of a GMC at 5 kpc from the centre (dust cloud D153). Contours are spaced by 50 mJy/beam (FWHM $0.9'' \times 0.74'' \simeq 3.95 \times 3.25$ pc, indicated in the lower right corner). The velocity channel of each field is marked in the upper left corner. J2000.0 coordinates are given with the lower left field. Although the structure is quite coherent in velocity space, it has significant spatial substructure. At least four individual clumps can be identified easily; no obvious kinematical or spatial structure is indicated in the corresponding survey data at 23'' resolution. Even for this quiescent cloud the virial masses determined from the two data sets differ significantly.

This is the first time that such a wide range of scales of the molecular gas emission can be investigated and searched for clues about its state, evolution into stars and mutual interactions with the other constituents of the ISM.

Acknowledgements

It is a pleasure to thank the PdBI staff and astronomers for the excellently performed observations. However, the tragical accidents stopped the completion of the high-resolution data set (shown in Fig. 3) among many other projects. This work is therefore dedicated to the memory of the victims.

A lot of work for the survey was done by Ph. Hoernes and in particular by Ch. Nieten, who set up (and efficiently uses) the present data reduction and analysis routines capable to handle the huge amounts of information fast enough.

References

Berkhuijsen E. M., Bajaja E., Beck, R.: (1993) *Astron. & Astrophys.* **279**, 359
Braun R.: (1991) *Astron. & Astrophys.* **372**, 54
Brinks E., Bajaja E.: (1986) *Astron. & Astrophys. Suppl. Ser.* **169**, 14
Brinks E., Shane W.W.: (1984) *Astron. & Astrophys. Suppl. Ser.* **55**, 179
Devereux N. A., Price R., Wells L. A., Duric N.: (1994) *Astron. J.* **108**, 1667
Hodge P. W.: (1981), *Atlas of the Andromeda Galaxy*, University of Washington Press, Seattle and London
Neininger N.: (1999), in V. Ossenkopf et al. (eds.): The Physics and Chemistry of the Interstellar Medium GCA-Verlag, Herdecke, p. 42
Neininger N., Guélin M., Ungerechts H., Lucas R., Wielebinski, R.: (1998) *Nature* **395**, 871
Pellet A., Astier N., Viale A., et al.: (1978) *Astron. & Astrophys. Suppl. Ser.* **31**, 439
Ryden B. S., Stark A.A.: (1986) *Astrophys. J.* **305**, 823