Cold Massive Molecular Clouds in the Inner Disk of M31

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ABSTRACT

We present new interferometric $^{12}\text{CO}(1-0)$ and single-dish $^{12}\text{CO}(3-2)$ observations of the central parts of D478, a large (> 200 pc) dark dust cloud located in a quiescent region of the inner disk of M31 where single-dish $^{12}\text{CO}(1-0)$ and $^{12}\text{CO}(2-1)$ observations were previously obtained. Only a small fraction (< 15%) of the $^{12}\text{CO}(1-0)$ flux previously detected in this region with the single-dish telescope is recorded by the interferometer. Most of the $^{12}\text{CO}(1-0)$ emission must therefore have the appearance of a smooth surface with very little structure on scales smaller than $\approx 25''$ (85 pc). Together with the earlier $^{12}\text{CO}(1-0)$ and $^{12}\text{CO}(2-1)$ single-dish results the new $^{12}\text{CO}(3-2)$ data are in good agreement with LTE predictions for optically thick lines at $T_{\text{ex}} = T_{\text{kin}} = 3.5$K. These results rule out the conventional model for these clouds consisting of warm clumps with a low filling factor (as would be the case if they resembled Galactic GMCs) and confirm that large, massive, cold molecular clouds exist in the inner disk of M31 with kinetic temperatures close to that of the cosmic microwave background. Such extremely low temperatures are likely to be a consequence of the low heating rate in these particular regions of M31, where very little massive star formation is occurring at present.

From the $^{12}\text{CO}$ line profile widths we estimate the Virial mass surface density of D478 to be $80 – 177 \, M_\odot \, \text{pc}^{-2}$. This is a factor 7 – 16 times larger than the value obtained by multiplying the $^{12}\text{CO}$ profile integrals with the conventional “X-factor”.


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1. Introduction

Unlike the annular region of prominent star formation at $8 < R_{\text{gal}} < 11$ kpc, the inner disk of M31 ($R_{\text{gal}} < 7$ kpc) contains very little of the classical tracers of massive star formation such as H\textsc{ii} regions and young clusters (e.g. Baade & Arp 1964). It is also nearly devoid of emission from the usual tracers of the cool interstellar medium such as H\textsc{i} (e.g. Brinks & Shane 1984) and CO (e.g. Dame et al. 1993). This situation is remarkable because prominent dust “arms” are visible throughout the inner disk of M31 (Baade 1963), and hundreds of dust clouds have been catalogued in these regions by Hodge (1980a, 1980b).

Should we conclude that there is no interstellar gas associated with these dust clouds? Could all the gas be frozen out on grain surfaces? Or is the gas present but just in a physical state which we cannot easily detect?

Using the IRAM 30-m radio telescope, Allen & Lequeux (1993) and Loinard, Allen & Lequeux (1996) detected faint but broad $^{12}\text{CO}(1-0)$ and $^{12}\text{CO}(2-1)$ profiles associated with several dust clouds in the inner disk of M31. Although these clouds obey the same size – line width relationship as Galactic Giant Molecular Clouds (GMCs), thereby suggesting similar masses, their $^{12}\text{CO}(1-0)$ luminosities are typically only $1/10$ that of Galactic GMCs with the same line widths, and their $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ line intensity ratios are unusually low. Two of these clouds, designated D268 and D478 in the catalog by Hodge (1980a), were subsequently observed in $^{13}\text{CO}$ with the 30-m telescope (Allen & Lequeux 1994); the $^{12}\text{CO}/^{13}\text{CO}$ ratio ($\approx 10$) confirmed that, in spite of their faintness, the $^{12}\text{CO}$ lines are optically thick. Equilibrium chemistry and radiative transfer calculations (Allen et al. 1995) further showed that the observed CO brightnesses are consistent with optically-thick lines emerging from a very low-temperature extensive medium. Such low temperatures can be understood as resulting from a lack of obvious heat sources (UV photons and cosmic ray primaries) in the inner disk of M31, a likely consequence of the very low rate of massive star formation there.

An alternative model for the observed CO emission in the inner disk of M31 follows from detailed studies of Galactic GMCs. In that picture the CO emission emanates from a collection of small, warm clouds, unresolved by the 30-m single-dish observations. The faintness of the CO emission results from the small area filling factor within the beam of the 30-m telescope. The large line widths would then have to be ascribed to random motions of these clouds driven by some process which is not related to the mass derived from the virial theorem. Because warm, thermalized clouds should have $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ line ratios of $\approx 1.0$, the observed values of $\lesssim 0.5$ would have to be a result of subthermal excitation conditions in a medium of low volume density. Unlike the case for cold, extended gas, this interpretation leads to the conclusion that only small amounts of molecular gas are present in the inner disk of M31.

We have carried out two new complementary observing programs in order to test these contrasting views. First, using the Millimeter Wave Array at the Caltech Owens Valley Radio Observatory\(^2\) (OVRO), we have obtained an aperture synthesis image of a $\approx 1'$ field within D478 at a resolution of $\approx 5''$ in the $^{12}\text{CO}(1-0)$ line. If the CO flux detected by the 30-m observations is coming from spatially compact components, they ought to be easily visible in the synthesis image with peak brightnesses of several Kelvins. If, on the other hand, the emission is mostly smooth, little or none of it will be recorded in the OVRO synthesis image. Second, we have obtained $^{12}\text{CO}(3-2)$ spectra at the center of D478 and at a reference position in the bright star-forming ring of M31 with the James Clerk Maxwell Telescope\(^3\) (JCMT). Owing to its higher critical density, the 3-2 transition should enable us to determine whether subthermality is the cause of the low 2-1/1-0 ratios.

2. Observations

Radial velocities in this paper will refer to the Local Standard of Rest (LSR); for comparison with other observations made in the Heliocentric system (HEL) we note that, at the position of M31, these systems are related by $V_{\text{HEL}} = V_{\text{LSR}} - 4.3$ km s$^{-1}$. Positions are measured as offsets $\Delta\alpha = 15 \times (\alpha - \alpha_0) \times \cos(\delta)$ and $\Delta\delta = \delta - \delta_0$ from the nominal center of M31 at $\alpha(1950.0) = 00^{h}40^{m}00^{s}, \delta(1950.0) = 40^\circ59'43''$.\(^2\)

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\(^3\)The JCMT is operated by the Royal Observatories on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.
2.1. The OVRO observations

The interferometer observations were taken with the 6-element Millimeter Wave Array at OVRO between 1996 December 8 and 1997 January 28. The spectrometer was a digital autocorrelator providing 32 MHz of available bandwidth at a spectral resolution of 1 MHz; at 115 GHz, this yields a velocity coverage of 83 km s\(^{-1}\) and a velocity resolution of 2.6 km s\(^{-1}\). A single field of view (HPBW \(\approx 65''\)) was observed centered on the position of D478 as defined by Allen & Lequeux (1993) at offset position \(\Delta \alpha = +245''\) and \(\Delta \delta = +473''\). The data were calibrated at Caltech using the software system developed by Scoville et al. (1993) for the Millimeter Wave Array. The instrumental passband was derived from integrations on an artificial noise source obtained at the beginning of each track. Phase and amplitude gains were calibrated using observations of 0133+476 obtained every half-hour throughout the observations, and the absolute flux density scale (accurate to 20\%) was calibrated using observations of Uranus and Neptune obtained at the beginning and/or end of each track. Corrections for atmospheric absorption were made continuously using the standard chopper-wheel method, which is also used at the IRAM 30-m telescope. After calibration, the flux density we recorded for 0133+476 is 2.0 Jy at 115 GHz, in excellent agreement with the values obtained for that source with the 30-m telescope at the end of 1996 (Ungerechts 1997, private communication). This gives us confidence that the flux density scales at OVRO and at the 30-m telescope are the same to within about 10\%.

The OVRO data were imaged in AIPS using natural weighting of the visibilities and some tapering. CLEANed to the 1'' resolution (50 mJy beam\(^{-1}\) \(\approx 0.15K\)), and restored with an elliptical gaussian beam of 6.8'' \(\times\) 4.6'' FWHM (PA = -27'). The OVRO array does not record short-spacing visibility data; the shortest baseline obtained during our observing run was 15 meters which, allowing for forshortening during the observation, provided visibility data down to \(\approx 3490\)\(\lambda\). A source smaller than \(\approx 10''\) will therefore be essentially fully recorded in our OVRO visibility measurements (\(V > 0.90\)), but a source larger than 50'' will be virtually absent (\(V < 0.10\))\(^4\). The restoration process will therefore produce channel maps with an estimate of that part of the source brightness distribution which has structure on angular scales \(\lesssim 25''\).

2.2. The JCMT observations

The CO(3-2) spectra were obtained with the JCMT on 1995 July 20. At 345 GHz, the HPBW of the JCMT is 15'', and the main beam efficiency \(\eta_{\text{mb}} = 0.58\). The data were obtained in position-switching mode, and the backend was the Dwingeloo Autocorrelation Spectrometer providing 760 MHz of available bandwidth at a spectral resolution of 756 kHz; at 345 GHz, this yields 650 km s\(^{-1}\) of velocity coverage with a resolution of \(\approx 0.5\) km s\(^{-1}\). However, because the passband of the frontend was only \(\approx 700\) MHz, the useful range was limited to about 600 km s\(^{-1}\). Since the observed profiles are about 15 – 30 km s\(^{-1}\) wide, the data were Hanning-smoothed to 2 km s\(^{-1}\) to enhance the signal-to-noise ratio. We observed both the center of D478, at \(\Delta \alpha = +245''\) and \(\Delta \delta = +473''\), and a reference position “M31ref” in the bright star-forming ring at \(\Delta \alpha = +1359''\), \(\Delta \delta = +679''\). These two positions were previously observed in the \(^{12}\)CO(1-0) and \(^{12}\)CO(2-1) lines with the 30-m telescope (Allen & Lequeux 1993, Loinard et al. 1996).

During the previous 30-m observations, we obtained data at positions in a small 5-point cross with 12'' spacing. The central spectrum was observed twice, once at the beginning of the cycle (hereafter S1), and once at the end (hereafter S6). In between, we obtained spectra at the 4 flanking fields (hereafter S2, S3, S4 and S5). The 6 spectra can be combined to smooth the CO(2-1) to different resolutions, using the equation \(S = [0.5(S_1+S_6)+\alpha(S_2+S_3+S_4+S_5)]/(4\alpha + 1)\). With \(\alpha = 0.5\), the 30-m CO(2-1) spectra can be smoothed to the resolution of the 30-m telescope at 115 GHz (23'', corresponding to 75 pc), and with \(\alpha = 0.17\) to the 15'' resolution of the JCMT at 345 GHz.

3. Results and Discussion

3.1. Structure of the CO(1-0) emission in the OVRO images

All of the emission detected in the OVRO synthesis is confined to the 9 central image channels, as shown in Figure 1. Note that the circles drawn on each channel map indicate the 23'' beam of the 30-m telescope at 115 GHz, not the 65'' OVRO field of view. A double source is clearly resolved in channels b-d at the
center of the map, and an additional elongated source is seen in the north-west part of the field in channels 1 – i. Figure 1j shows contours of the total CO(1-0) emission detected in the OVRO maps; in Figure 2 these contours are drawn over an optical image of this part of M31 obtained from the Digitized Sky Survey5. The contours of the emission detected at OVRO are elongated in the same direction as an underlying dust feature, but the CO contours are significantly narrower than the dust lane.

3.2. The fraction of the 30-m flux in the OVRO map

After smoothing the OVRO channels maps to the 23′′ resolution of the IRAM 30-m telescope at 115 GHz, we corrected these maps for attenuation by the primary beam of the array elements, and extracted the velocity profiles at the positions we had previously observed with the 30-m telescope. The results are shown in Figure 3. The thin-lined histograms in this Figure show the 30-m data, and the thick lines the OVRO data. Representative gaussian fits are also shown. The spectrum labelled (+245″; +473″) corresponds to the circles drawn at the centers of the channel maps in Figure 1; the spectrum at (+245″; +497″) is located a full beamwidth to the north.

It is clear from Figure 3 that only a small fraction of the 30-m flux has been recovered in the OVRO maps. At the central position (+245″; +473″) the 30-m flux is 66.5 Jy km s⁻¹, but the integral under the OVRO spectrum is only 9.9 Jy km s⁻¹ or 15% of the 30-m flux. At the northern position (+245″; +497″) the 30-m flux is 68.5 Jy km s⁻¹, whereas the OVRO flux is 5.1 Jy km s⁻¹ or only 7.5% of the 30-m flux. It is also clear that the OVRO profiles are qualitatively different from those recorded by the 30-m. The component near -85 km s⁻¹ in Figure 3 apparently has ∼ 10 – 30% of its energy in spatial structures ≤ 25″, whereas the component near -75 km s⁻¹ must be very smooth on these angular scales.

3.3. Excitation conditions from the 30-m and JCMT spectra

We shall see momentarily that the CO lines emanating from D478 are consistent with high optical depth. For optically-thick lines, the observed brightness temperature T_b is related to the excitation temperature T_{ex} by:

\[ T_b = T_0 \left( \frac{1}{e^{T_{ex}/T_0} - 1} - \frac{1}{e^{T_0/T_{bg}} - 1} \right) \]  (1)

where T_{bg} = 2.73K is the temperature of the cosmic microwave background (Mather et al. 1994), and T_0 = hν/k, where ν is the frequency of the observed transition.

We have re-analyzed the 30-m ¹²CO(1-0) and the ¹²CO(2-1) spectra first reported by Allen & Lequeux (1993) using an improved method of combining the individual observations, i.e. weighting by the inverse square of the actual r.m.s. noise in each spectrum rather than by the integration time. The results (at 23″ resolution) are shown in Figure 4a. The spectra differ slightly from the original results published in Figure 2b of Allen & Lequeux, although the differences are minor. The peak on our revised ¹²CO(1-0) spectrum is now ∼ 0.05K lower, while the ¹²CO(2-1) spectrum peak is ∼ 0.07K higher6. In Figure 4b we show the ¹²CO(2-1) data at 15″ and add our new JCMT ¹²CO(3-2) result. The procedure used to obtain the smoothed profiles is described in §2.2.

Since for Galactic GMCs the area filling factor over the observing beam is generally < 1, it is usual to estimate the excitation temperature from the ratios of two CO lines (assuming the filling factor is the same for both lines). From Figure 4a the 2-1/1-0 line ratio for the -85 km s⁻¹ component at the center of D478 is 0.5, for which Equation 1 yields an excitation temperature of T_{ex} = 3.5K. For this excitation temperature, Equation 1 predicts a ¹²CO(1-0) brightness temperature of 0.6K, and a ¹²CO(2-1) brightness temperature of 0.3K, which are exactly the peak temperatures observed. We conclude that the filling factor within a 23″ area is ≈ 1, consistent with the conclusion drawn earlier from the OVRO data that most of the ¹²CO(1-0) emission from D478 emanates from a smooth surface. The narrow ridge of emission in the OVRO map of Figure 2 is indicative of a slightly warmer region; it appears to be just resolved in the 5″ OVRO map,

5The optical image is from a short-exposure V plate taken with the Palomar Schmidt telescope and digitized at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory.

6Note also that Allen & Lequeux used Heliocentric velocities.
with \(^{12}\text{CO}(1-0)\) peak brightness temperatures of 1 – 1.2K in a 5\(^\prime\) beam, corresponding to an excitation temperature of \(\approx 4K\).

Figure 4b shows the 30-m \(^{12}\text{CO}(2-1)\) profile (dashed line) smoothed to the 15\(^\prime\) resolution of the JCMT. We note that the amplitude and general shape of this profile is nearly the same as that of the 23\(^\prime\) \(^{12}\text{CO}(2-1)\) profile in Figure 4a, which is also consistent with a filling factor \(\approx 1\). For \(T_{\text{ex}} = 3.5K\), Equation 1 predicts that the \(^{12}\text{CO}(3-2)\) brightness temperature should be 0.1K, in excellent agreement with the observed JCMT spectrum (Figure 4b). From this we conclude that the \(^{12}\text{CO}(3-2)\) line is also thermalized, and that the excitation temperature in D478 is equal to the kinetic temperature of the molecular gas. The density of the molecular gas is apparently of the order of several thousand cm\(^{-3}\), the critical density for excitation of the CO(3-2) line. The combination of the OVRO \(^{12}\text{CO}(1-0)\) data with the 30-m and JCMT observations of the \(^{12}\text{CO}(1-0)\), \(^{12}\text{CO}(2-1)\) and \(^{12}\text{CO}(3-2)\) emission lines is consistent with the conclusion that D478 is a large, smooth, optically thick, thermalized molecular cloud at \(T_{\text{kin}} = T_{\text{ex}} \approx 3.5K\).

We now compare the results just obtained in D478 with similar observations of the reference position “M31ref” (\(\Delta \alpha = +1359\), \(\Delta \delta = +679\)) in the bright star-forming ring of M31. There, the excitation temperature deduced from the 2-1/1-0 ratio (Figure 5a) is 5K. But for \(T_{\text{ex}} = 5K\), Equation 1 predicts a \(^{12}\text{CO}(1-0)\) brightness temperature of about 1.9K; since the observed \(^{12}\text{CO}(1-0)\) profile has a peak amplitude of 0.75K, we expect the CO filling factor inside the 23\(^\prime\) beam of the 30-m telescope to be \(\approx 40\%\). Wilson & Rudolph (1993) observed the field around this position with the BIMA interferometer. They resolved the emission into several small sources and recovered virtually all the single dish flux density. At \(\Delta \alpha = +1359\), \(\Delta \delta = +679\), they detected one molecular cloud (M31-1, see their Figure 2), with size 14\(^\prime\) \(\times\) 17\(^\prime\). The corresponding filling factor in the 23\(^\prime\) beam of the 30-m telescope is then (14 \(\times\) 17)/(23 \(\times\) 23) = 45\%, in excellent agreement with what we have inferred from our observations. However, the JCMT data for this position in M31 can not be so readily reconciled; the 3-2/2-1 line ratio (Figure 5b) corresponds (Equation 1) to \(T_{\text{ex}} \approx 9K\); much higher than the value deduced from the 2-1/1-0 line ratio. It is possible that for this position, which is located in a region of massive star-formation, embedded sources heat the cloud from the inside, thereby enhancing the heating of the higher density regions. That no such additional heating is present in D478 is consistent with the apparent lack of active star formation in this region.

### 3.4. Mass Surface Density

It is clear that the conventional method of calculating the \(\text{H}_2\) mass from the \(^{12}\text{CO}(1-0)\) brightness (as summarized e.g. by Allen 1996 and in references given there) will fail for cold thermalized clouds like D478, for the simple reason that the \(^{12}\text{CO}(1-0)\) brightness vanishes as the cloud temperature descends towards that of the cosmic background at 2.73 K (cf. Equation 1). This disappearance of the \(^{12}\text{CO}(1-0)\) emission is, of course, quite independent of the total mass of molecular gas present. We are left with the Virial theorem as the only remaining method of estimating the underlying mass. For this method to work we need to have a tracer for the maximum extent of the turbulent velocities present in the gas contained within the telescope beam. The residual \(^{12}\text{CO}(1-0)\) emission profile remains useful for this purpose, even for cold clouds, assuming that the parts of the clouds which are warm enough to be detected have a range of velocities that is representative of the turbulence in the entire area covered by the telescope beam. In this picture, specific peaks in the total CO profile have no special significance; only the total velocity extent of the whole profile matters.

The virial mass \(M_{\text{vir}}\) of a cloud of radius \(R\) (in parsec), integrated line width \(\Delta v\) (FWHM in km s\(^{-1}\)), and a constant density distribution is (e.g. MacLaren et al. 1988) \(M_{\text{vir}}/M_{\odot} = 210 \times (\Delta v)^2 R\). Since D478 fills the 30-m telescope beam (FWHM = 23\(^\prime\) or 75 pc), we can calculate the mass surface density at e.g. the central position (+245\(^\prime\); +473\(^\prime\)) in Figure 3. At this position, the velocity profile width \(\Delta v = 25\) km s\(^{-1}\). In the spirit of the model we are using, the fact that the profiles in Figure 3 appear to be separable into two components is irrelevant. However, one correction which does need to be applied is to account for any contribution to \(\Delta v\) arising from a gradient of the rotational velocity field of M31 over the 23\(^\prime\) beam of the 30-m telescope. This contribution can be estimated from the model velocity field fitted to the 21-cm \(\text{H}_1\) synthesis of M31 by Brinks (1984, page 4-28); it is \(\approx 4\) km s\(^{-1}\) at the position of D478. This must be linearly subtracted from the observed profile width, leaving \(\approx 21\) km s\(^{-1}\). The mass surface density of D478 is therefore:
in the plane of M31, where we have taken the inclination of M31 to be $i = 77^\circ$.

An alternative model is to consider the two peaks in the velocity profile of D478 as two physically distinct “clouds”. We emphasize that the structure of D478 which we have deduced from our own data, namely, an extended cold cloud with a few localized warm regions on its surface, is not consistent with such an alternative model. Nevertheless, it is common to interpret velocity profiles in this way, and we give the result here for completeness. In that case, each of the two main components has $\Delta v \approx 10 \text{ km s}^{-1}$, and the mass surface density at the center of D478 would then be:

$$
\Sigma \approx 2 \times 210 \times \frac{(21)^2 \times \cos i}{(\pi \times 37.5)} \approx 177 \text{ M}_\odot \text{pc}^{-2} \ \ (2)
$$

Finally, we note that the conventional method of determining masses from CO profiles based on a CO-to-H$_2$ “conversion factor” $X = 1.9 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1}$ (e.g. Strong & Mattox 1996) yields a mass surface density of $\approx 11 \text{ M}_\odot \text{ pc}^{-2}$ including a correction factor of 1.36 for helium. This “X-factor” mass surface density is about an order of magnitude less than that deduced from the virial theorem. Magnani & Onello (1995) also found large variations (a factor 10 or more) in the conversion factor both for translucent and for dark clouds in the Galaxy. We conclude that this is an unreliable method of determining molecular masses and variations in molecular mass surface densities in galaxies.

4. Concluding Remarks

Our analysis of new $^{12}\text{CO}(1-0)$ interferometric observations, and of single-dish $^{12}\text{CO}(1-0)$, $^{12}\text{CO}(2-1)$ and new $^{12}\text{CO}(3-2)$ observations, confirms that the faint CO emission in the direction of D478 emanates from an extended, smooth, massive structure at very low kinetic temperature. These results are likely to apply to other dark clouds in the inner disk of M31. In contrast, the CO emission from the star-forming ring of M31 comes from smaller clouds with higher kinetic temperatures, as is the case for Galactic GMCs.

These cold, massive, molecular clouds we have identified in the inner disk of M31 appear to be quite different than Galactic GMCs. However, the observational differences do not necessarily have to reflect intrinsic structural differences, but could result from the same gas finding itself in a different environment, as has been suggested by Allen et al. (1995). Suppose the gas is an extensive, turbulent medium with a wide range of densities. In the absence of strong fluxes of UV photons (and cosmic rays) the low-density parts remain molecular and cold, and this medium will appear faint, smooth and extended in the CO lines, as is seen in D478. However, when subjected to an intense flux of UV photons (as would be the case for gas located near regions of massive star formation), the low density regions would be dissociated and the remaining high-density regions will be heated, so that the CO lines will appear to emanate from warm, high-density clumps. This could explain the situation for Galactic GMCs, and also for our reference position “M31ref” in the star-forming ring of M31.

The dust clouds in the inner disk of M31 constitute an excellent “laboratory” for the study of the large-scale physics of molecular gas. The relative scarcity of massive star-forming regions allows us to observe molecular clouds in somewhat simpler situations. D478 for instance, with its smooth appearance and apparent lack of embedded sources, is apparently close to the idealized case of an infinite plane-parallel cloud illuminated on one side by a flux of UV photons. Studies of a larger sample of such clouds with varying local conditions (nearby B stars, etc.) would be helpful in elucidating the interplay between the ISM and star formation, and may also provide a more complete view of the total molecular content of this galaxy.

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Fig. 1.— $^{12}$CO(1-0) emission recorded by the OVRO Millimeter Wave Array in the field of D478. The center of the field is at offset $\Delta \alpha = +245''$, $\Delta \delta = +473''$ from the nominal center of M31 at $\alpha(1950.0) = 00^h 40^m 00^s$, $\delta(1950.0) = 40^\circ 59' 43''$. The circle in each panel indicates the 23'' beam (FWHM) of the 30-m telescope at 115 GHz. The central (LSR) velocity of each channel is indicated in each panel. The maps have not been corrected for primary beam attenuation. The synthesized beam is $6.8'' \times 4.6''$ FWHM (PA = -27°) and is shown in the lower left corner of panel (j). Panels (a) to (i): The first contour and the contour interval are 100 mJy beam$^{-1} = 0.3$ K ($\approx 2\sigma$). Panel (j): Total emission detected by the OVRO array, obtained by integrating the channels (a) to (i). The first contour and the contour level are 0.78 Jy beam$^{-1}$ km s$^{-1}$. The 5 crosses in this panel correspond to the positions of the 5 spectra in Figure 3.

Fig. 2.— OVRO total $^{12}$CO(1-0) contours overlaid on a short exposure V image from the Digitized Sky Survey. The first contour and contour interval are 0.78 Jy beam$^{-1}$ km s$^{-1}$. The circle indicates the size of the OVRO field of view (65'' FWHM).

Fig. 3.— $^{12}$CO(1-0) spectra at 23'' resolution for 5 positions in the region of D478. The panel labelled (+245'';+473'') is the central position in Figure 1. The thin line histograms are the 30-m single-dish profiles, and the thick lines are the smoothed OVRO data. The y-axis is in Kelvins and is the same for all panels; the X axis is LSR radial velocity.

Fig. 4.— Panel (a): 23'' resolution 30-m $^{12}$CO(1-0) (full line) and $^{12}$CO(2-1) (dashed line) spectra at the center of D478 ($\Delta \alpha = +245''$, $\Delta \delta = +473''$). Panel (b): 30-m $^{12}$CO(2-1) (dashed line) spectrum smoothed to 15'' resolution of the JCMT, and JCMT $^{12}$CO(3-2) (dotted line) spectrum at the same position. The x-axis in both panels is LSR radial velocity.

Fig. 5.— Same as Figure 4, but for the reference position “M31ref” at $\Delta \alpha = +1359''$, $\Delta \delta = +679''$. 