ASTE observations of nearby galaxies: A tight correlation between CO(J=3–2) emission and Hα

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Abstract

Star formation rates (SFRs) obtained via extinction corrected Hα are compared to dense gas as traced by 12CO (J = 3–2) emission at the centers of nearby galaxies, observed with the ASTE telescope. It is found that, although many of the observed positions are dusty and therefore heavily absorbed at Hα, the SFR shows a striking correlation with dense gas in the form of the Schmidt law with an index 1.0. The correlation is also compared between gas traced by 12CO (J = 1–0) and application of Hα extinction correction. We find that dense gas produces a far better correlation with SFR in view of surface density values.

Key words: galaxies:ISM — galaxies:spiral — ISM:molecules — stars:formation

1. Introduction

The present knowledge of star formation on galactic scales in relation with its precursor gas is generally expressed by the Schmidt law (Schmidt 1959),

\[ SFR \propto \rho^N \]  \hspace{1cm} (1)

where SFR is the star formation rate, \( \rho \) the gas density, and \( N \) the Schmidt law index, expressing the efficiency of star formation from gas. Often written also in terms of surface averaged quantities, equation (1) relates two physical values SFR and \( \rho \) which are generally spatially decoupled when observed locally, and connected in a spatially averaged sense. The connection between the two values also has a time averaged nature, namely the formation timescale of massive stars. Therefore, in order to obtain valid physical suggestions from the Schmidt law, we must derive these two values based on measurements which express conditions that are spatially and temporally connected as much as observations allow.

Previous observations of molecular gas have been conducted mainly in the 12CO (J = 1–0) line, tracing cold gas which constitutes the bulk of galactic molecular clouds. However, Kohno et al. (1999) have shown that a tracer of denser gas, HCN, shows a better spatial correlation with star forming regions. Observations of dense gas tracers such as HCN (Gao and Solomon 2004) and higher transition CO lines like 13CO (J = 2–1) (Braine et al. 1993; Böker et al. 2003) and 12CO (J = 3–2) (Mauersberger et al. 1999; Yao et al. 2003; Narayanan et al. 2005) are becoming accessible, and it is of interest how these tracers of dense show up in terms of the Schmidt law.

The calibration of SFR becomes an issue under these circumstances, where virtually all observational inquiry of the Schmidt law using dense gas has resorted to FIR as the SFR calibrator. This in part owes to the fact that FIR data from the IRAS satellite is abundant, and that many of the sample galaxies observed in dense gas tracers (HCN and higher CO transitions) were selected according to FIR luminosity. However, we must bear in mind that the SFR must be calibrated using massive stars. The SFR derived from FIR luminosity can only trace star formation over \( \sim 10^8 \) years, because of its contamination from extended dust heated by the interstellar radiation field (Kennicutt 1998), which can amount to a significant fraction of the FIR luminosity (e.g., Hirashita et al. 2003).

This results in overestimation of the SFR, and also becomes a bottleneck in improving the temporal connection of gas and star formation. Another practical shorthand is that the angular resolution of IRAS data is commonly several arcminutes; too large to infer physics from the correlation between dense gas tracer data, which are typically tens of arcseconds in angular resolution. The most reliable massive SFR tracer to date is the Hα luminosity tracing star formation over several \( 10^6 \) years, whose correlation with dense gas, surprisingly has not been checked. The main reason is that Hα is weak in dusty galaxies such as those observed in dense gas tracers, due to the extinction within the galaxies. It is important therefore not only to acquire the Hα luminosity of these galaxies, but to accurately estimate the amount of extinction.

The main objective and result of this Letter is to examine the correlation between 12CO (J = 3–2) tracing warm...
dense gas (typically ~ 30K), and extinction corrected Hα luminosity tracing accurately the SFR, both in surface averaged densities.

2. Observation

Observation of the $^{12}$CO ($J = 3–2$) at 345GHz was conducted using the Atacama Submillimeter Telescope Experiment (ASTE) (Ezawa et al. 2004; Kohno 2005), a 10m single dish located in the Atacama desert of altitude 4800m in Pampa La Bola, Chile. Observations were remotely made from an ASTE operation room of the National Astronomical Observatory of Japan (NAOJ) at Mitaka, Japan, using a network observation system N-COSMOS3 developed by NAOJ (Kamazaki et al. 2005).

The sample was selected to be able to compare the dense gas quantity and its relation with star formation, in both normal and starbursting galaxies. The galaxies were selected so that most them have readily accessible and extinction correctable Hα data. Another limitation for the samples was that their velocity width had to be under 350 km s$^{-1}$, chosen so that the emission fits within the bandwidth 445 km s$^{-1}$ of the backend, allowing for baseline subtraction. Table 1 lists the observed samples. The galaxies were observed only at their central position, and the resolution FWHM of ASTE ($22''$) corresponds to a linear size of $\sim$3 kpc for a typical sample distance of 30 Mpc.

The observations were conducted in August 2005, in fair weather conditions, using a double sideband cooled SIS mixer. Calibration was done using the standard chopper wheel method. Backend was a 1024 channel digital spectrometer with 512 MHz bandwidth and frequency resolution of 0.5 MHz, corresponding to a velocity resolution of 0.43 km s$^{-1}$. The resulting velocity bandwidth is 445 km s$^{-1}$. Typical system temperatures at 345 GHz ranged from 180K to 300K. Pointing was checked every several hours using Uranus or Mars, and was found to be accurate to $\sim 1''$.

Obtained data were reduced with NEWSTAR, an AIPS based software, used commonly at Nobeyama Radio Observatory (NRO). After flagging bad spectra, first to second order baselines were subtracted, then smoothed to a velocity resolution of typically 15 to 20 km s$^{-1}$. $T_A^\circ$ was then converted to $T_{mb}$ via $T_{mb} = T_A^\circ / 0.6$, were 0.6 is the main beam efficiency of the ASTE telescope. The resultant integrated intensity of the galaxies are listed in table 1.

3. Results

The integrated intensity $I_{CO}(J = 3–2) = \int T_{mb}dv$ can be converted to surface gas density using the conversion factor $X_{CO}$ such that $\Sigma \propto X_{CO} I_{CO}$, assuming that $^{12}$CO ($J = 3–2$) uniquely traces dense gas. However, gas temperature can contribute to $^{12}$CO ($J = 3–2$) emission and will introduce complications. In order to circumvent this difficulty, we use $I_{CO}(J = 3–2)$ hereafter, regardless of what it implies physically. Errors for the values listed in table 1 were calculated using

$$\delta I_{CO} = \sigma \sqrt{\Delta V_{CO} \delta V} \quad [\text{K km s}^{-1}]$$

where $\sigma$ is the r.m.s. noise in $T_{mb}$, $\Delta V_{CO}$ the full line width, and $\delta V$ the velocity resolution (15 or 20 km s$^{-1}$).

The obtained spectra are presented in figure 1.

All galaxies were detected except for NGC 520, but we attribute this to NGC 520’s line width of 500km s$^{-1}$ Solomon et al. (1992).

3.1. SFR

The SFR was derived for the sample galaxies where possible, using narrow band Hα imaging data from Young et al. (1996). Flux within the ASTE beam was calculated using task “apphot” on the FITS images using IRAF software. The SFR surface density $\Sigma_{SFR}$ was then calculated using the formulation by Kennicutt (1998), and corrected for inclination by a factor $\cos i$.

$$\Sigma_{SFR} \ (M_\odot \ pc^{-2} \ yr^{-1}) = 7.9 \times 10^{-43} \frac{L(H\alpha)}{S} \cos i \quad (\text{ergs s}^{-1} \ pc^{-2})$$

where $S$ is the projected area of the observing beam.

The SFR derived in this way was then corrected for internal extinction into $\Sigma_{SFR}^{corr}$ when possible, by dust using $E(B-V)$ magnitudes derived from $H\alpha/H\beta$ ratio given in Ho et al. (1997). Combined with equation 3, we obtain the extinction corrected SFR $\Sigma_{SFR}^{corr}$.

In order to compensate for the lack of data, we compiled $^{12}$CO ($J = 3–2$) from other sources. Table 2 lists these sources, along with the SFR derived as above where possible.

3.2. Schmidt Law

Figure 2 shows the obtained Schmidt law between extinction corrected Hα and $^{12}$CO ($J = 3–2$). For comparison, we also show the relation between $^{12}$CO ($J = 1–0$) and Hα. $^{12}$CO ($J = 1–0$) data are taken from similar resolution ($16''$ or $22''$) surveys by Komugi et al. (in preparation), Braine et al. (1993), and Nishiyama and Nakai (2001). Apparently, a combination of extinction corrected SFR and dense gas gives a better correlation.

Table 3 gives the Schmidt law index $N$ and correlation coefficient. In all cases, the index $N$ of the Schmidt law is found to be effectively 1, consistent with previous studies which use total luminosity in comparing the two values representing gas and SFR (Gao and Solomon 2004; Yoo et al. 2003; Böker et al. 2003), even though we use surface densities which are more indicative of the intrinsic properties of the samples.

3.3. Inclination Correction

An effect we must consider when using surface averaged values is the inclination of the target galaxy, where the surface density is derived by multiplying the luminosity by $\cos i$. However, inclination is generally defined from its global morphology, and hence is not always indicative of the disk in its central kpc, as in this case. The central region may be thick or clumpy, so that corrections for
Table 1. Observed Galaxies

| Galaxy  | RA   | DEC  | Morphology | $D$  | $i$  | $T_{\text{CO}}^\text{3-2}$ | log $\Sigma_{\text{SFR}}$ | log $\Sigma_{\text{SFR}}^{\text{corr}}$ |
|---------|------|------|------------|------|-----|-----------------|-----------------|----------------|-------|
| NGC 157 | 00 32 14.45 | -08 40 18.8 | SABbc | 35   | 49  | 6.9±0.5      | -7.58          |
| NGC 520 | 01 21 59.79* | +03 31 55.9 | Pec    | 45.5 | 66  | no detection  |
| NGC 925 | 02 24 16.89 | +33 21 18.9 | SABd   | 14.3 | 53  | 1.1±0.5      | -7.70          |
| NGC 1022 | 02 36 03.99 | -06 53 34.1 | SBa    | 30.1 | 34  | 45±1.0       |
| NGC 1088 | 02 40 07.05 | -00 13 31.6 | SAb    | 22.7 | 40  | 157±4.5      |
| NGC 1084 | 02 43 32.11 | -07 47 17.4 | SAc    | 28.1 | 59  | 19±1.7       |
| NGC 1087 | 02 43 31.80* | -07 47 06.0* | SAb    | 36.9 | 49  | 10.3±0.5     |
| NGC 7479 | 23 02 26.39 | +12 03 10.3 | SBc    | 52.1 | 38  | 21.3±0.9     |
| NGC 7625 | 23 17 60.00 | +16 57 05.6 | SAbpec | 37.3 | 22  | 24.3±0.8     |
| NGC 1082 | 23 18 00.60* | +16 57 15.0* | SAbpec | 37.3 | 22  | 11.3±0.5     |

Col.(1): Galaxy name. Col.(2)(3): Coordinates from NED. Many were observed also at optically defined coordinates from Dressel & Condon (1976), used in the $^{12}$CO ($J = 1-0$) survey by Komugi et al. (in preparation), marked *. For NGC 157 and NGC 925, coordinates from both NED and Dressel & Condon (1976) match. Col.(4)(5): Morphology, distance, and inclination in degrees, as listed in Young et al. (1995). Col.(7) Observed integrated intensity of $^{12}$CO ($J = 3-2$), converted to main beam temperature units. Col.(4)(5): SFR and extinction corrected SFR, respectively, as explained in text.

Table 2. Sample Galaxies.

| Galaxy  | Ref. | $T_{\text{CO}}^\text{3-2}$ | log $\Sigma_{\text{SFR}}$ | log $\Sigma_{\text{SFR}}^{\text{corr}}$ |
|---------|------|-----------------|-----------------|-------|
| NGC 891 | 1    | 24±2           | -9.01           | -7.64          |
| NGC 2146 | 1 | 193            | -6.88           | -5.76          |
| NGC 2276 | 2 | 12.2±0.2       | -7.21           | -6.39          |
| NGC 2903 | 2 | 63±2           | -6.78           | -6.37          |
| NGC 3079 | 2 | 183±3.2        | -8.14           | -6.06          |
| NGC 3351 | 1 | 28             | -6.73           | -6.33          |
| NGC 3627 | 1 | 8.8±1          | -7.23           | -6.63          |
| NGC 4088 | 1 | 26±1           | -7.73           | -6.89          |
| NGC 4102 | 1 | 31             | -6.97           | -6.04          |
| NGC 5907 | 1 | 6±0.7          | -9.43           | -8.18          |
| NGC 6946 | 1 | 46±2           | -7.00           | -5.92          |
| NGC 7331 | 1 | 17.5±1.2       | -7.49           | -7.27          |
| NGC 7541 | 1 | 7±1            | —               | —              |

Col.(1): Galaxy name. Col.(2): References. 1 refers to Mauersberger et al. (1999); 2 refers to Narayanan et al. (2005). Both were observed at the HHT, with an angular resolution of 22". Col.(3): Integrated intensity of $^{13}$CO ($J = 3-2$) line, in main beam temperature units. Col.(4)(5): SFR and extinction corrected SFR, respectively.

Table 3. Least Squares fit

| Gas tracer | Ext. Corr. | $N$ | $r^2$ |
|------------|------------|-----|-------|
| $^{12}$CO ($J = 3-2$) | Yes | 0.93±0.12 | 0.91 |
| $^{12}$CO ($J = 1-0$) | Yes | 1.05±0.19 | 0.83 |
| $^{12}$CO ($J = 3-2$) | No | 0.92±0.17 | 0.79 |
| $^{12}$CO ($J = 1-0$) | No | 0.93±0.22 | 0.70 |

Col.(1): Tracer used for dense gas. Col.(2): “No” for no Hα extinction correction, “Yes” for correction applied as explained in text. Col.(3)(4): Schmidt law index $N$ and correlation coefficient, from a least squares fitting. For all gas tracers, the lower row is for no inclination correction.

Col.(1): Galaxy name. Col.(2): References. 1 refers to Mauersberger et al. (1999); 2 refers to Narayanan et al. (2005). Both were observed at the HHT, with an angular resolution of 22", same as ASTE. Col.(3): Integrated intensity of $^{13}$CO ($J = 3-2$) line, in main beam temperature units. Col.(4)(5): SFR and extinction corrected SFR, respectively.

Col.(1): Tracer used for dense gas. Col.(2): “No” for no Hα extinction correction, “Yes” for correction applied as explained in text. Col.(3)(4): Schmidt law index $N$ and correlation coefficient, from a least squares fitting. For all gas tracers, the lower row is for no inclination correction.
Fig. 1. $^{12}$CO ($J = 3–2$) spectra of the galaxy centers observed at ASTE. Spectra with an asterisk are those observed at positions as explained in table 1.

Fig. 2. The obtained Schmidt law for the sample galaxies, using combinations of gas ($^{12}$CO ($J = 1–0$) and $^{12}$CO ($J = 3–2$)), and SFR with and without internal extinction correction. The lower right hand panel is best correlated, with $N = 1.0$ shown as the best fit line.

beam is more clumpy than disky. The resulting Schmidt law will be biased towards $N = 1$, because the gas and SFR densities decrease equally along a slope of 1. The right hand side of figure 3, is the same for values uncorrected for inclination. We do not see any trend with inclination, which is physically more plausible.

From these views, we conclude that a correction for inclination of cos $i$ is not completely justified; figure 4 show the Schmidt law for all values uncorrected for inclination. The variance of the residuals for a best fit is given in table 3, and in this case also we see that the use of $^{12}$CO ($J = 3–2$) and extinction corrected Hα improves the fit greatly.

4. Discussion

We have shown for the first time that $^{12}$CO ($J = 3–2$) has a striking correlation with Hα derived SFR. Assuming that $^{12}$CO ($J = 3–2$) indeed traces dense gas, this implies that Hα may be a valid SFR tracer even in dense and dusty regions. Dense gas $^{12}$CO ($J = 3–2$) also correlates better with recent star formation compared to $^{12}$CO ($J = 1–0$).

Interpreting this result in a qualitative manner is easy. Assuming that star formation occurs where gas density exceeds a certain value, we can expect that $^{12}$CO ($J = 3–2$) is more spatially and temporally connected to star formation compared to $^{12}$CO ($J = 1–0$). By using Hα as a SFR tracer, the spatial connection (resolution) and temporal connection (traces SF over $10^6$ years) are even more
improved. This improvement should show up in terms of the Schmidt law.

Using H\textalpha, we have circumvented the need to use global gas and SFR in expressing the Schmidt law, which is known to introduce a size effect. Larger galaxies tend to be more luminous in any wavelength: therefore producing a correlation between gas and SFR without any other physical reasons (see Stark et al. 1986). The resolution of H\textalpha imaging allowed us to meaningfully derive surface density values, whereas using the IRAS data may force us to compare spatially decoupled gas and SFR within the large beam.

The Schmidt law index \( N \), however, should be treated with care. The correction for extinction can be applied only to detectable emission, and not the intrinsic total H\textalpha emission. This is not unique to recombination lines, but to all star formation tracers where extinction plays a role. In that light, The observed Schmidt law index is always an underestimate, where in our case the effect may be strong because our study focuses on the central regions of dusty galaxies. This is in concord with the literature, where the widely accepted value of 1.4 (e.g., Kennicutt 1998) is considerably higher than our derived value of \( \sim 1.0 \).

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