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Kinematical Properties of Giant Molecular Clouds and Star Forming Efficiency

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Abstract

We are interested in the relationship between interacting luminous galaxies and their star forming efficiency. However, because of the limitation of available data, we have studied kinematic properties of giant molecular clouds (GMCs) associated with the star-forming regions in our Galaxy. We found that the star-forming efficiency (*SFE*) is correlated not only with the gas density (n), but also strongly with the velocity dispersion (σ_v) and the mass of a GMC. We obtained a modified Schmidt's law by fitting the derived *SFE* to the gas density and velocity dispersion to be: $SFE \propto n^{\alpha}\sigma_v^{\beta}$, where the indices were determined as $\alpha \sim 0.03$ and $\beta \sim -3.3$. This implies that stars are born more efficiently in a quiet cloud than in a disturbed cloud, and that the *SFE* is strongly dependent on the kinematical property of gas clouds.

Key words: Interstellar: clouds — Interstellar: H II regions — Stars: formation

1. Introduction

Observations of interacting luminous galaxies at various frequencies have shown that recent star bursts are the sources of energy supply to the luminosity (Joseph 1990). Spectroscopy and imaging observations have shown that this star-forming activity is strongly enhanced by tidal interactions (Lavery, Henry 1988).

In particular, such strong interactions as collisions and mergers seem to effectively trigger starbursts. Under such conditions, it is natural to think that molecular clouds in the galaxies are kinematically disturbed, resulting in an increase in the velocity dispersion within individual clouds. This suggests that the star-forming efficiency (*SFE*) would be positively correlated to the velocity dispersion of individual clouds.

We have not yet obtained sufficient data about individual molecular clouds in external galaxies for such study. Thus, we cannot directly research the correlation of kinematical properties of molecular clouds with the star-forming rate (*SFR*) and *SFE* for external galaxies. On the other hand, many observations of molecular clouds and star-forming regions (or H II regions) have been obtained in the Milky Way. We use these observational results and discuss placed correlation between the physical properties of molecular clouds and *SFR* or *SFE*, with a particular attention on the internal motions and mass of clouds.

We describe the used data in section 2, and our analysis method and results in section 3. The implications of the results are discussed in section 4.

2. Data

We used the data of molecular clouds by Solomon et al. (1987). They surveyed the ^{13}CO emission line with the FCRAO 14 m antenna at 110 GHz, with a HPFW of 47″. The survey spacing was 3′ (over the range $l = 18°$–$54°$).

For the H II regions we use the data by Downes et al. (1980), who observed the H110α recombination line with the Effelsberg 100 m telescope at 4.8 GHz with a HPFW of 2.′6. See the references for details concerning the data sets.

Since we selected molecular-cloud — H II region pairs from these data, the distance between a cloud and an H II region is smaller than 10 parsec. Table 1 shows the position and size of selected samples. Column 1 is the serial numbers; v is the radial velocity along the line of sight; θ is the angular extent of H II region ; the θ_l and θ_b are extents of a molecular cloud in l and b directions; and D is the distance to a molecular cloud.

The size of selected H II regions is several parsecs, the density is 100 H cm^{-3}, and the mass is several $10^2 M_{\odot}$. The molecular clouds extend for several tens pc, the density is 1000 H$_2$ cm^{-3}, and the mass is from $10^5 M_{\odot}$ to $10^6 M_{\odot}$. Therefore, most of the clouds are Giant Molecular Clouds (GMCs).

We show the physical condition of the samples in table 2, where *V* means volume, *EM* is emission measure,

Table 1. Position and size of selected samples.

No.	H II regions				Molecular clouds					
	l (deg.)	b (deg.)	v (km s^{-1})	θ (arcmin)	l (deg.)	b (deg.)	v (km s^{-1})	δ_l (deg.)	δ_b (deg.)	D (kpc)
1	8.362	−0.303	36.0	4.5	8.40	− 0.30	37.0	0.32	0.15	5.7
2	10.617	−0.364	− 2.0	3.2	10.60	−0.40	−2.0	0.17	0.11	6.5
3	12.204	−0.116	25.0	3.3	12.20	−0.10	23.0	0.04	0.04	16.3
4	12.807	−0.204	35.5	2.8	12.80	−0.20	32.0	0.29	0.16	4.1
5	13.875	0.282	53.0	2.7	13.90	0.30	49.0	0.12	0.12	5.2
6	13.998	−0.128	31.5	3.3	14.00	−0.10	26.0	0.10	0.08	3.2
7	15.032	−0.687	11.5	4.5	15.00	−0.70	20.0	0.16	0.09	2.5
8	18.143	−0.289	52.0	2.8	18.15	−0.30	54.0	0.25	0.18	4.9
9	18.881	−0.493	67.0	7.5	18.85	0.05	50.0	0.11 .	0.09	14.4
10	20.733	−0.087	57.0	4.5	20.75	−0.10	59.0	0.08	0.06	13.8
11	22.982	−0.356	78.0	4.5	23.00	−0.40	74.0	0.29	0.18	12.8
12	23.421	−0.214	104.0	3.8	23.40	−0.25	102.0	0.08	0.07	11.0
13	23.956	0.152	80.3	2.7	23.95	0.15	79.0	0.06	0.04	5.8
14	24.217	−0.053	89.0	3.5	24.20	−0.05	88.0	0.09	0.05	11.9
15	24.484	0.211	117.5	7.5	24.45	0.25	120.0	0.22	0.18	9.1
16	24.517	−0.233	96.0	4.4	24.50	−0.25	101.0	0.09	0.08	10.9
17	25.294	0.307	45.0	3.3	25.25	0.30	47.0	0.08	0.09	14.4
18	25.766	0.211	111.6	5.5	25.80	0.25	109.0	0.25	0.09	9.0
19	27.276	0.148	33.0	2.9	27.25	0.15	33.0	0.09	0.05	15.2
20	27.491	1.189	35.5	3.5	27.50	0.20	36.0	0.04	0.04	15.0
21	28.600	0.015	93.0	6.5	28.60	0.05	100.0	0.09	0.09	8.8
22	30.776	−0.029	90.0	4.1	30.80	−0.05	92.0	0.20	0.24	6.8
23	31.401	−0.259	90.0	3.4	31.40	−0.25	88.0	0.05	0.04	10.7
24	33.914	0.111	98.5	2.6	33.90	0.10	106.0	0.20	0.08	8.3
25	34.254	0.144	53.0	2.8	34.25	0.10	53.0	0.19	0.15	3.7
26	37.763	−0.216	61.0	3.1	37.75	−0.20	60.0	0.05	0.08	11.6

T_e is electron temperature, and f expresses integrated flux at 4.8 GHz. We denote the virial mass as M_V, and the number density of H_2 molecules as n_{H_2}.

3. Analysis

Based on the data given in tables 1 and 2, we derive SFR and SFE, and investigate the correlation with the kinematical properties of molecular clouds.

3.1. *Correlation with SFR*

SFR within a star-forming region is expressed as

$$SFR \propto \frac{N_{\mathrm{OB}}}{T_{\mathrm{OB}}}, \tag{1}$$

where N_{OB} and T_{OB} means the number of OB stars and the lifetime, respectively. If we assume that the lifetime of OB stars is a few 10^7 years and is universal, we may assume that

$$SFR \propto N_{\mathrm{OB}}. \tag{2}$$

To determine SFR, we first estimate how many OB stars exist from the relation

$$4\pi r^2 n_{\mathrm{H}} \frac{dr}{dt} = N_{\mathrm{UV}} - n_{\mathrm{i}} n_{\mathrm{e}} \alpha_{\mathrm{r}} \mathrm{V}. \tag{3}$$

Here $n_{\mathrm{H}}, n_{\mathrm{i}}$, and n_{e} are the number density of H I, H II, and electrons, respectively, where $n_{\mathrm{i}} \simeq n_{\mathrm{e}}$, and $\alpha_{\mathrm{r}} = 4 \times 10^{-13}$ is the recombination rate; N_{UV} is UV photon flux from the OB stars, and r is the radius of H II region. If dr/dt is sufficiently small,

$$N_{\mathrm{UV}} \simeq n_{\mathrm{e}}^2 \alpha_{\mathrm{r}} V. \tag{4}$$

The emission measure is expressed by n_{e}, and the line-of-sight depth of the H II region is R,

$$EM = \int_0^R n_{\mathrm{e}}^2 dx \simeq n_{\mathrm{e}}^2 R. \tag{5}$$

Hence,

$$N_{\mathrm{UV}} \propto V \frac{EM}{R}. \tag{6}$$

Assuming that the depth (R) and size (r) of the H II region are of the same order, we obtain

Table 2. Physical condition of the samples.

No.	H II regions					Molecular clouds		
	V [pc^3]	$EM(10^4)$ [cm^{-6} pc]	T_e [K]	f [Jy]	$V(10^4)$ [pc^3]	σ_v [km s^{-1}]	$M_v(10^4)$ [$M_\odot$]	$n_{H_2}(10^3)$ [cm^{-3}]
1	51.92	2.10	7300	2.4	0.14	3.90	66.50	1.08
2	27.68	23.00	10500	6.8	0.05	3.00	27.90	1.31
3	478.80	7.60	7000	2.7	0.02	3.90	34.60	4.22
4	4.65	320.00	7900	30.0	0.05	6.80	140.60	6.61
5	8.51	91.00	7500	4.1	0.02	3.00	19.70	2.74
6	3.62	8.40	5800	3.0	0.00	2.30	5.30	7.60
7	4.38	300.00	9100	344.5	0.00	3.00	9.20	11.06
8	7.95	59.00	5800	5.5	0.08	5.70	117.00	3.48
9	3875.44	4.30	5900	18.3	0.20	3.20	51.20	0.59
10	736.76	7.40	5900	8.5	0.06	3.70	45.70	1.75
11	587.92	3.40	7800	3.9	1.71	7.60	588.60	0.77
12	224.69	14.00	6000	9.4	0.04	4.90	68.90	4.17
13	11.81	55.00	5600	2.5	0.00	2.90	8.40	12.13
14	222.28	1.90	7300	0.9	0.04	3.000	24.90	1.59
15	978.04	2.60	4700	10.8	0.40	6.60	274.90	1.56
16	339.38	4.20	8500	4.5	0.05	5.00	80.80	3.45
17	330.13	2.50	7500	0.9	0.12	4.50	86.20	1.60
18	373.13	4.00	6200	8.1	0.19	6.60	204.90	2.48
19	263.50	8.60	7400	1.2	0.07	4.40	68.80	2.10
20	445.17	6.40	7200	3.0	0.01	2.90	17.50	2.74
21	575.76	2.10	8300	6.3	0.03	5.20	74.50	5.07
22	66.67	72.00	6000	62.2	0.22	5.20	140.40	1.43
23	148.13	4.40	6000	1.8	0.01	2.90	14.10	4.32
24	30.92	27.00	5300	1.1	0.09	4.20	64.50	1.70
25	3.42	150.00	8700	13.4	0.02	2.60	46.40	6.39
26	143.06	16.00	8400	3.9	0.03	5.20	68.90	5.74

$$N_{\rm UV} \propto EM \times S. \tag{7}$$

On the other hand, the UV photon flux is proportional to the number of OB stars, $N_{\rm UV} \propto N_{\rm OB}$, which is on the order of $N_{\rm UV} \simeq 10^{49}$–$10^{50}$, estimated from the data in the tables. Since, for instance, the luminosity (L) of O5 stars is $L \simeq$ *several* $\times 10^5 L_\odot$ ($L_\odot \simeq 3.85 \times 10^{33}$ erg s^{-1}), the selected H II regions include a few such high mass stars. Now, we have

$$SFR \propto N_{\rm OB} \propto N_{\rm UV} \propto EM \times r^2, \tag{8}$$

where the size of H II region is given by $r = D\theta$. Thus, the dimension of SFR is cm^{-6} pc^3 yr^{-1}. We plot the mass of molecular clouds, velocity dispersion, and H$_2$ number density against the obtained SFR using equation (8) in figures 1, 2, and 3, respectively.

We cannot find any clear correlations in the plots, except that the lower envelope of the SFR–$n_{\rm H_2}$ plot (figure 3) appears to show a correlation suggesting the law.

3.2. Correlation with SFE

We are most interested in how the efficiency of SFR depends on the physical properties of molecular clouds. We, therefore, discuss the correlation between SFE and the kinematic properties of the molecular clouds. SFE is calculated by

$$SFE \propto \frac{N_{\rm OB}}{M_{\rm V}} \propto \frac{N_{\rm UV}}{M_{\rm V}} \propto \frac{EM \times r^2}{M_{\rm V}}. \tag{9}$$

The dimension of SFE is cm^{-6} pc^3 $M_\odot^{-1}$ $(10^7$ yr$)^{-1}$. We plotted the calculated SFE against the mass, velocity dispersion, and number density of H$_2$ in figures 4, 5, and 6, respectively.

Figures 4 and 5 clearly show an inverse correlation. It may be natural to imagine that stars more actively form in high-mass and large molecular clouds than in small clouds. In the figure 4, however, we reached and opposite result. SFE decreases with the mass of giant molecular clouds. The solid line in figure 4 is the best-fit line by the least squares method, and the correlation is given by

$$SFE \propto \frac{EM \times r^2}{M_{\rm V}} \simeq 1.5 \times 10^5 M_{\rm V}^{-0.78}. \tag{10}$$

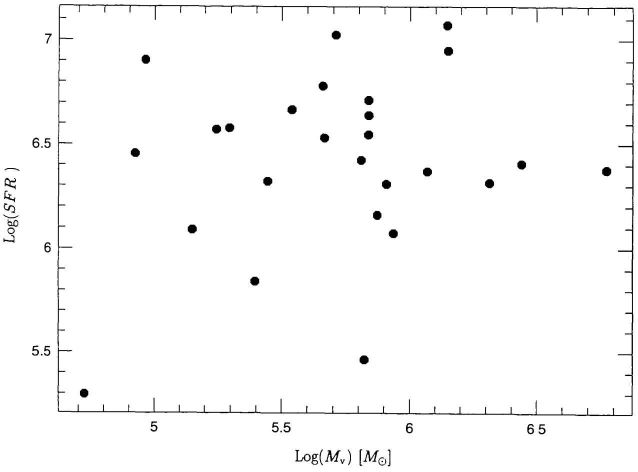

Fig. 1. Plot of the star-formation rate (*SFR*) against the mass of associated molecular clouds.

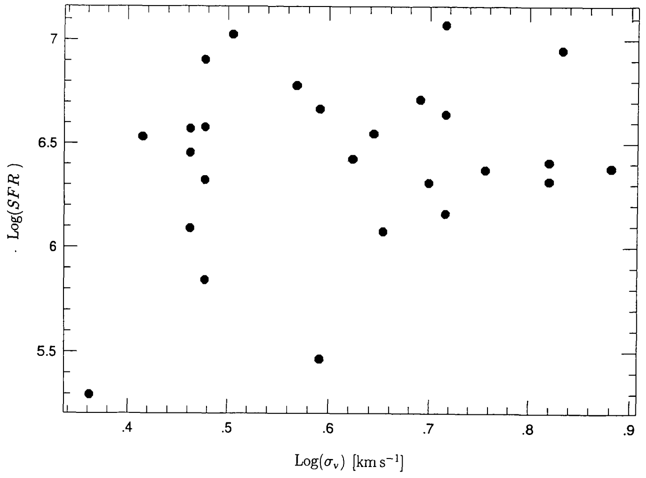

Fig. 2. Plot of the *SFR* against the velocity dispersion in associated molecular clouds.

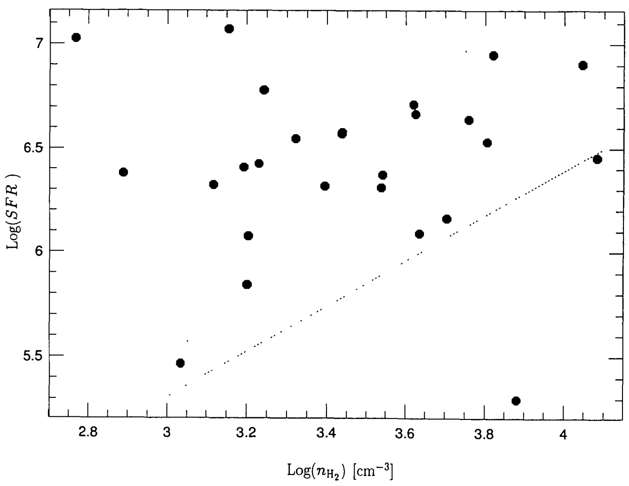

Fig. 3. Plot of the *SFR* against the molecular gas density of associated molecular clouds.

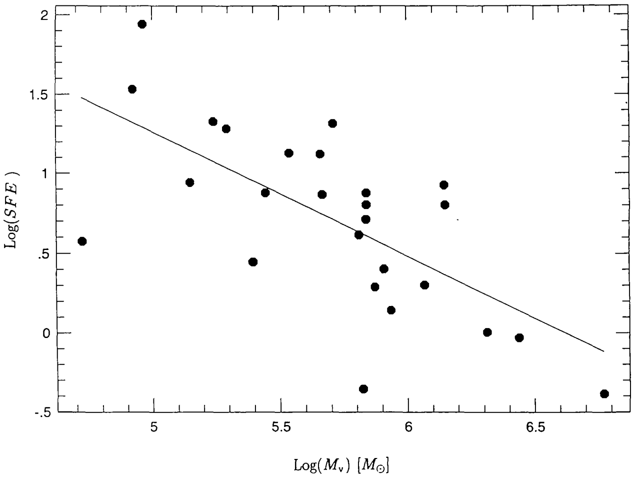

Fig. 4. Plot of the *SFE* against the mass of an associated molecular cloud. Note the inverse correlation of *SFE* against the cloud mass.

We can also see an inverse correlation between *SFE* and velocity dispersion in molecular clouds from figure 5. We calculated the correlation function,

$$SFE \propto \frac{EM \times r^2}{M_V} \simeq 100 \times \sigma_v^{-2.1}. \tag{11}$$

Using the typical value of L_{O5} (mentioned before), i.e., $L_\odot \simeq 10^5 L_\odot$, we can rewrite this function as,

$$SFE\ [N_{O5}\ M_\odot^{-1}\ (10^7\mathrm{yr})^{-1}] \simeq 8.0 \times 10^{-2} \times \sigma_v^{-2.1}. \tag{12}$$

This second result was also not expected from the argument described in section 1. We thought that the higher is the internal motion, such as that due to collisions, the more easily do clumps form stars; therefore, *SFE* increases with the velocity dispersion of molecular clouds. However, our result indicates that stars more effectively form in more quiet molecular clouds.

Thirdly, from figure 6, we obtained a positive correlation between *SFE* and n_{H_2}, which is a natural consequence of the Schmidt law. The solid line in this figure,

$$SFE \simeq 0.02 \times n_{H_2}^{0.69}, \tag{13}$$

is the best-fit line.

4. Discussion

We have shown that *SFE* is inversely correlated with the velocity dispersion of molecular clouds, and may summarize that the fit environment to form stars is a dense and quiet molecular cloud. It seems difficult to

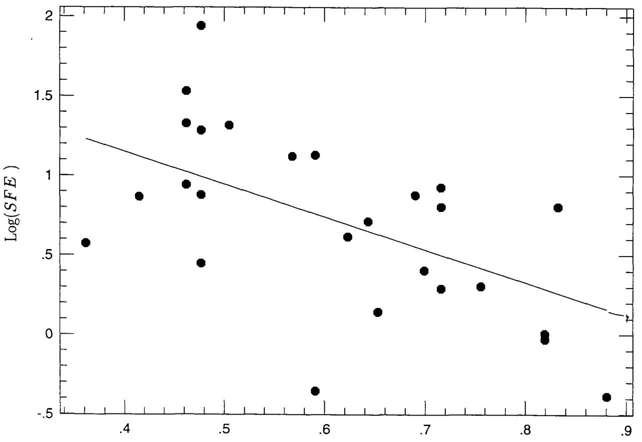

Fig. 5. Plot of the *SFE* against the velocity dispersion in an associated molecular clouds. Note the inverse correlation of *SFE* against the velocity dispersion.

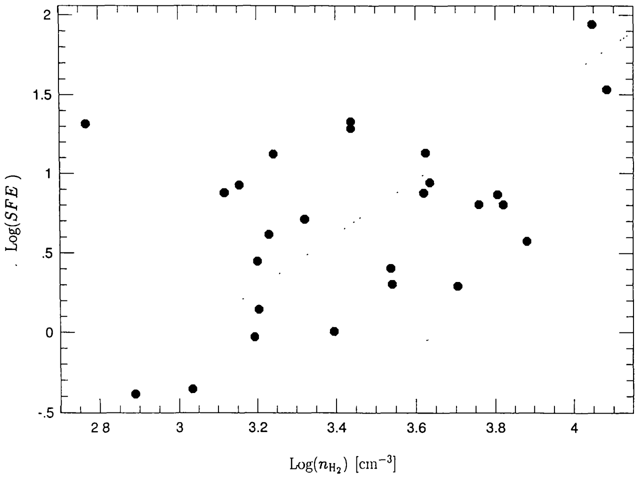

Fig. 6. Plot of the *SFE* against the molecular gas density of an associated molecular cloud. Note the Schmidt law-like correlation.

relate our result directly to the star-burst phenomenon in interacting galaxies. Considering that the distances between the selected H II regions and molecular clouds are only several parsecs, it will be reasonable to consider that the stars were born in the neighbor of the molecular clouds to form the H II regions. As we can see from figure 5, *SFE* decreases as the velocity dispersion in molecular clouds increases. A simple explanation is that active motion of molecular gas suppresses an efficient gravitational collapse to form stars.

Heyer et al. (1996) studied ^{12}CO and ^{13}CO of molecular clouds associated with optical H II regions, and showed that most of the molecular mass of the clouds resides within extended, low-density regions well removed from the localized sites of star formation. An inspection of the large-scale kinematics and distribution of mass shows that most of the kinematic energy is contained within the relative motions of resolved substructures in the giant molecular clouds. We may thus have related *SFE* to acquired physical properties of molecular clouds already affected effected by new-born stars.

On the other hand, we found only a weak correlation between *SFE* and the gas density. The higher is the number density in a molecular cloud, the higher is *SFE*, but only slightly. This implies that the usual Schmidt law is insufficient for relating *SFR* (*SFE*) with the properties of molecular clouds. We may thus try to make up a modified Schmidt law, i.e.

$$SFE \propto n^{\alpha}\sigma_v^{\beta}, \tag{14}$$

where n is density of the cloud. A least-squares fit to the apparent correlation shown in figures 5 and 6 by regarding the density and velocity dispersion as being independent variables gives indices of $\alpha \sim 0.69$ and $\beta \sim -2.1$. However, since the density and velocity dispersion are not separated in the relation, it is more reasonable to fit the *SFE* by three-variable least-squares method as

$$\log\, SFE = \alpha\, \log\, n + \beta\, \log\, \sigma_v + \gamma, \tag{15}$$

where γ is a constant.

In order for the summation $S = \Sigma_i[(\log\ SFE)_i - \alpha(\log\ n_{\mathrm{H}_2})_i - \beta(\log\ \sigma_v)_i - \gamma]^2$ to be minimized, we obtained the least-squares fit values for the indices as $\alpha \sim 0.03$ and $\beta \sim -3.3$. The standard error is 2.68 and the correlation coefficient is 0.64. We, thus, obtain a modified Schmidt law as

$$SFE\ [\mathrm{cm}^{-6}\ \mathrm{pc}^2\ M_{\odot}^{-1}\ (10^7\ \mathrm{yr})^{-1}] \simeq 1.4 \times n_{\mathrm{H}_2}^{0.03}\ \sigma_v^{-3.3}. \tag{16}$$

For example, if we assume O5 stars which have $L_{\mathrm{O5}} \sim 10^5 L_{\odot}$, the above equation can be rewritten, as

$$\begin{aligned} &SFE\ [N_{\mathrm{O5}}\ (M_{\odot})^{-1}\ (10^7\ \mathrm{yr})^{-1}] \\ &\quad \simeq 1.1 \times 10^{-3} \times n_{\mathrm{H}_2}^{0.03}\ \sigma_v^{-3.3}. \end{aligned} \tag{17}$$

We emphasize that the *SFE* is extremely sensitive to the kinematics of a gas cloud, much more sensitive than to the density, in the sense that the lower the velocity dispersion of a cloud, the higher the star-forming efficiency.

References

Downes D., Wilson T.L., Bieging J., Wink J. 1980, A&AS 40, 379
Joseph R.D. 1990, in Dynamics and Interactions of Galaxies ed R. Wielen (Springer-Verlag, Berlin, Heidelberg) p132
Heyer M., Carpenter J., Ladd E. 1996, ApJ 463, 630
Lavery R.J., Henry J.P. 1988, ApJ 330, 596
Solomon P.M., Rivolo A.R., Barrett J., Yahil A. 1987, ApJ 319, 730