SUPERBUBBLE EVOLUTION INCLUDING THE STAR-FORMING CLOUDS: IS IT POSSIBLE TO RECONCILE LARGE MAGELLANIC CLOUD OBSERVATIONS WITH MODEL PREDICTIONS?

SERGEI SILICH\textsuperscript{1} AND JOSÉ FRANCO\textsuperscript{2}

Received 1999 January 15; accepted 1999 April 19

ABSTRACT

Here we present a possible solution to the apparent discrepancy between the observed properties of LMC bubbles and the standard, constant-density bubble model. A two-dimensional model of a wind-driven bubble expanding from a flattened giant molecular cloud is examined. We conclude that the expansion velocities derived from spherically symmetric models are not always applicable to elongated young bubbles seen almost face-on because of the LMC orientation. An observational test to differentiate between spherical and elongated bubbles seen face-on is also discussed.

Subject headings: ISM: bubbles — ISM: clouds — ISM: structure — Magellanic Clouds

1. INTRODUCTION

Since the discovery of large shells and holes of neutral hydrogen in the Magellanic Clouds (see McGee & Milton 1966 and Westerlund & Mathewson 1966 for the LMC, and Hindman 1967 for the SMC), the Milky Way (Heiles 1979), and M31 (Brinks & Bajaja 1986), the study of interstellar bubbles has been extended to several nearby galaxies (see recent reviews by Brinks & Walter 1998 and Thilker 1998). The optical counterpart of these objects are the H\textsc{ii} ring-shaped nebulae (e.g., Boulesteix et al. 1974; Davies, Elliot, & Meaburn 1976; Sivan 1977; Pellet et al. 1978; Meaburn 1980; Lozinskaya & Sitnik 1988), which are powered by young massive stars, and many H\textsc{ii} bubbles are actually delineated by them. Thus, a paradigm for bubble evolution driven by energy injection from massive stars was developed during the 1960s and 70s by Pikelner (1968), Avedisov (1972), and Weaver et al. (1977). These original analytical models have been extended during the last two decades with two- and three-dimensional numerical simulations by Bisnovatyi-Kogan & Blinnikov (1982), Mac Low & McCray (1988), Palous (1992), and Silich (1992); see reviews by Tenorio-Tagle & Bodenheimer (1988) and Bisnovatyi-Kogan & Silich (1995).

A number of important processes affecting the expansion of shells have been studied during this time, including the effects of blowout and dynamical instabilities in decreasing density gradients (Mac Low, McCray, & Norman 1989; Tenorio-Tagle et al. 1990; Garcia-Segura & McLow 1995a, 1995b), gravitational instabilities (McCray & Kafatos 1987; Ehlerova et al. 1997), ambient magnetic fields (Tomisaka 1990, 1998; Ferriere, Mac Low, & Zweibel 1991), galactic differential rotation (Palous 1992; Silich & Moreno 1996; Moreno, Alfaro, & Franco 1999), radiation pressure from field stars (Elmegreen & Chiang 1982; Franco et al. 1991a), the impact of supernova fragments in expanding superbubble shells (Franco et al. 1993), the role of hydrodynamic ablation and thermal evaporation of ambient clouds (Hartquist et al. 1986; Arthur & Henney 1996; Silich et al. 1996), and photoionization from the central stars (Comeron 1997).

In principle, then, one could compare the predictions of a variety of different models (i.e., the resulting bubble shapes, expansion velocities, column densities, X-ray luminosities, etc.) with the available observational data for holes and shells (e.g., Chu & Mac Low 1990; Silich et al. 1996b; Mashchenko, Thilker, & Braun 1998; Thilker, Braun, & Walterbos 1998). A direct comparison with observations, however, presents several problems, because it is difficult to constrain most of the relevant model parameters (for instance, the energy input rate and the original density structure). Several steps have been taken recently to address some of these questions, and additional problems with the applicability of models have emerged.

Detailed studies of the OB stellar content in associations in the Milky Way and the Magellanic Clouds are now possible with CCD photometry (see Saken et al. 1992; Oey 1996a), and, in combination with stellar evolution models, they provide limits to the mechanical energy input rate. These rates have been used to compare LMC bubble observations with the predictions of the "standard" model (i.e., a spherically symmetric shell evolving in a constant-density medium). The comparisons indicate that the standard model cannot reproduce the properties of a number of well-observed cases (Rosado 1986; Oey & Massey 1995; Oey 1996b). In particular, the collection of bubbles observed in the LMC exhibit two different sets of objects with conflicting size-velocity relations. Given that the observed shell sizes are well known, the problem can be reduced to the existence of objects with expansion velocities that are either too high or too low to be explained by the simple standard model. For the low-velocity objects, the discrepancy could probably be explained by errors in the estimation of either the input wind power or the ambient gas density (Oey 1996b). For the high-velocity objects, however, the observed nebular expansion velocities ($V_{\text{exp}} \sim 25$ km s$^{-1}$) are at least a factor of 2 larger than the expected values (Oey 1996b). Neither the density gradient in the disk of the LMC nor possible variations of the initial mass function (or non-coeval star formation) can resolve this discrepancy (Oey 1996b).

A possible solution to this problem is suggested by the fact that the LMC has a moderate inclination angle, of about 27° (Crampton 1979), and the shells are viewed with a nearly face-on orientation. For face-on galaxies, the density gradient along the z-direction can influence the bubble expansion along the line of sight, increasing the observed
gas velocities. The effects of the gradient are more relevant in big spirals with a thin disk, and less important in dwarf irregulars with extended H I layers (see the discussion by Brinks & Walter 1998). However, the overall effect becomes certainly pronounced, even for dwarfs with very thick layers of H I, if one takes into account the presence of the parent giant molecular cloud (GMC) that gives birth to the perturbing stellar group and controls the initial bubble expansion: the high mass concentration within the parent GMC induces strong changes in the dynamics of shocks and can accelerate and generate fragmentation in the resulting shells (see Franco et al. 1989, 1990, 1997; Garcia-Segura & Franco 1996). A recent semianalytical study of a model with a sharp density contrast indicates that the bubble kinematics could reach the required velocity values (Oey & Smedley 1998), and the presence of the parent cloud provides the required density gradient. In this paper we focus on the dynamics and observational manifestations of relatively young bubbles, with modest sizes (below 100 pc), which originate from associations embedded inside GMCs. The paper is organized as follows. Section 2 describes the basic input model and numerical scheme. Section 3 contains the results from numerical calculations, and these results are discussed in § 4.

2. THE CLOUD DENSITY STRUCTURE AND MODEL ASSUMPTIONS

For a spherically symmetric isothermal self-gravitating cloud in equilibrium, the gas density declines as $r^{-2}$ (where $r$ is the distance from the cloud center). For cylindrical (dislike) self-gravitating clouds with infinite radius, on the other hand, the isothermal density stratification along the $z$-axis varies as sech$^2(z/H)$ (where $H$ is the scale height). Obviously, other cloud models with different morphologies result in different functional forms for the density stratifications. Here we use a simplified model to simulate the density distribution of a flattened, two-dimensional GMC. The two-dimensional stratification is defined in the cylindrical coordinate system ($r$, $\phi$, $z$), with the origin at the cloud center. The cloud has a constant-density core, with density $\rho_c$, and the density decreases as a power law until it reaches the value of the ambient medium, $\rho_{\text{ISM}}$. For simplicity, here we assume a constant value for $\rho_{\text{ISM}}$; the initial GMC density distribution is then defined as

$$
\rho = \begin{cases} 
\rho_c, & \text{for } \left(\frac{r}{R_c}\right)^2 + \left(\frac{z}{Z_c}\right)^2 \leq 1, \\
\rho_c \left[ \left(\frac{r}{R_c}\right)^2 + \left(\frac{z}{Z_c}\right)^2 \right]^{w/2}, & \text{for } \left(\frac{r}{R_c}\right)^2 + \left(\frac{z}{Z_c}\right)^2 \leq \xi^{2/w}, \\
\rho_{\text{ISM}}, & \text{for } \left(\frac{r}{R_c}\right)^2 + \left(\frac{z}{Z_c}\right)^2 > \xi^{2/w},
\end{cases}
$$

(1)

where $\xi = \rho_c / \rho_{\text{ISM}}$ is the ratio of the cloud core density to the ISM gas density, $w$ is the power-law index, and $R_c$ and $Z_c$ are the characteristic scale heights for the cloud density distribution in the $r$- and $z$-directions, respectively. The resulting maximum cloud extent along any of these axes is defined by $r_\text{cl} = R_c \xi^{1/w}$ and $z_\text{cl} = Z_c \xi^{1/w}$.

The appropriate range of values for the cloud parameters can be derived from observational results. For instance, using the spherically symmetric case ($R_c = Z_c$), we can derive the core radius from the condition that the observed shell mass, $M_{\text{obs}}$, is contained within the observed shell radius, $R_{\text{obs}}$. For a given core density, the observed mass is simply given by

$$
M_{\text{obs}} = M_c + 4\pi \int_{R_c}^{R_{\text{obs}}} \rho(r)r^2 dr,
$$

(2)

where $M_c$ is the core mass, and the resulting core radius follows from the equation

$$
\left(\frac{R_c}{R_{\text{obs}}}\right)^3 - \frac{3}{w} \left(\frac{R_c}{R_{\text{obs}}}\right)^w + \frac{3 - w}{w} \frac{3M_{\text{obs}}}{4\pi R_{\text{obs}}^2 \rho_c} = 0.
$$

(3)

For simplicity, we use $w = 2$ (which corresponds to a self-gravitating and isothermal sphere in the $R_c = Z_c$ case), and the radius $R_{\text{obs}}$ is set equal to 40 pc. The mass $M_{\text{obs}}$ is considered in the range $2-5 \times 10^4 M_\odot$, to be consistent with the observed shell masses (Oey 1996b). The solution of equation (3), which is solved numerically at the beginning of the runs, is used as the characteristic scale height $R_c$ for the two-dimensional models, and the characteristic scale in the $z$-direction is reduced to a half of this value, $Z_c = R_c/2$. Finally, we take the cloud core number density, $n_c$, as a free parameter and explore density values in the range from 10 to $10^2$ cm$^{-3}$. We designate the models as A or B depending on whether the resulting cloud mass, $M_{\text{obs}}$, is equal to 2 or $5 \times 10^4 M_\odot$, respectively. Thus, for a given core density value, they correspond to small and large clouds, respectively. The resulting GMC density distributions for both types of models, A and B, are illustrated in Figure 1, where the last isodensity contour represents the cloud boundary.

Assuming that the initial GMCs are in hydrostatic equilibrium, self-gravity defines the total pressure at the cloud center. Again, using the spherically symmetric model as an illustrative case, the total pressure at the cloud center is

![Figure 1](image-url)

FIG. 1.—Gas density distribution for the model GMCs. Panels a and b show the isodensity contours for models A2 and B2, respectively. The value of log $n$ is indicated at each contour.
where ergs s~1 is maintained at 6 zmann’s constant (the ambient gas temperature is main-

The thermal pressure inside an adiabatic bubble, on the other hand, is

\[ p_{\text{th}}(r) = \frac{(4.14 \rho)^{1/3} L_{0}^{2/3}}{2 \pi^{3/2} \rho} \left( \frac{9}{32 \pi^{2}} G \right)^{1/3} \]

where \( r_s \) is the bubble radius, and \( L_0 \) is the mechanical energy input rate. The thermal pressure inside a bubble with radius \( R_c \) (i.e., a supershell emerging from the cloud core) exceeds the total pressure at the cloud center, \( p_{\text{th}}(r_s = R_c) > p_c \), when the core densities are below the reference value

\[ n_{\text{ref}} = \left( \frac{1}{4.14} \right)^{1/3} \left( \frac{9}{32 \pi^{2}} G \right)^{1/3} \left( \frac{L_0}{R_c^{5/2}} \right)^{1/5} \]

\[ \simeq 2 \times 10^4 L_{36}^{2/3} \left( \frac{1 \text{ pc}}{R_c} \right)^2 \text{ cm}^{-3} \]

where \( L_{36} = L_0 / 10^{36} \text{ erg s}^{-1} \). Thus, for densities below \( n_{\text{ref}} \), one can neglect the cloud gravity and pressure during the early expansion, and for simplicity we maintain only the external ISM pressure, \( p_{\text{ISM}} = k_{\text{ISM}} T_{\text{ISM}} \), where \( k \) is Boltzmann’s constant (the ambient gas temperature is maintained at \( 6 \times 10^3 \text{ K} \) throughout the calculations).

The simulations are performed with the three-dimensional code described by Bisnovatyi-Kogan & Silich (1995) and Silich et al. (1996), which is based on the thin-layer approximation. In the present set of calculations, the energy input rate is assumed to be constant during the runs. Shell evaporation into the bubble due to thermal conduction is taken into account (see Silich et al. 1996), and this is the only source for mass injection into the cavity. The calculations of the X-ray luminosities are done with the table for the specific X-ray emissivities described by Suchkov et al. (1994). Several runs had been done taking into account possible fragmentation of the shell via the Rayleigh-Taylor (R-T) instability, as discussed by Silich & Tenorio-Tagle (1998). The model parameters used in the runs are summarized in Table 1.

3. THE RESULTS

Figure 2 shows the resulting morphologies for models A and B (left and right panels, respectively). As expected, after expanding inside the constant-density core, the remnant is elongated along the \( z \)-axis, where the density gradient is steepest. The deviation from the spherical morphology is already apparent after 2 Myr of evolution (Figs. 2b and 2e). At late evolutionary times, a dense, compressed ringlike belt is formed at the midplane of the cloud, as can be seen in Figure 2c (at 4 Myr) for model A2. In fact, model A2 presents a well-defined hourglass shape after 4 Myr, with two semispheres separated at midplane, as described in the analytical approach of Kontorovich & Pimenov (1997). Model B2, on the other hand, evolves more slowly in the higher density cloud, and after 4 Myr (Fig. 2f) it looks similar to model A2 after 2 Myr (Fig. 2b). Despite the large differences in the \( z \)-direction between the elongated and spherical models, the midplane radii are similar for both types of models.

The evolutionary tracks for the two sets of cloud models are shown in Figures 3 and 4 (models A and B, respectively). For comparison, Figures 3a and 4a show the radii and expansion velocities (solid and dotted lines, respectively) for the corresponding spherical bubble cases. Figures 3b, 3e, 4b, and 4e illustrate the kinematics for elongated bubbles as

| Model | \( n_c \) (cm\(^{-3}\)) | \( n_{\text{ISM}} \) (cm\(^{-3}\)) | \( M_f \) (10\(^4\) \( M_\odot \)) | \( R_c \) (pc) | \( Z_c \) (pc) | \( R_{cl} \) (pc) | \( L_{\text{GB}} \) (10\(^{36}\) ergs s\(^{-1}\)) |
|-------|----------------|----------------|----------------|-------------|---------|-------------|----------------|
| A1... | 2.4    | 2.4   | 2    | ... | ... | ... | 5 |
| A2... | 10    | 0.2   | 2    | 12.6 | 6.3   | 89.5 | 5 |
| A3... | 100   | 0.2   | 2    | 3.7 | 1.8   | 82.1 | 5 |
| B1... | 5.9   | 5.9   | 5    | ... | ... | ... | 5 |
| B2... | 10    | 0.2   | 5    | 22.5 | 11.25 | 159.0 | 5 |
| B3... | 100   | 0.2   | 5    | 5.9 | 2.95 | 132.5 | 5 |
they should be seen in a face-on galaxy; solid lines represent the bubble radii in the midplane of the host galaxy (i.e., along the $r$-axis), while the dotted lines correspond to the shell velocity in the $z$-direction. The kinematical properties for edge-on galaxies are shown in Figures 3c, 3f, 4c, and 4f. In this case, the dotted lines represent the expansion velocities in the galactic midplane, and the solid and dashed lines show the bubble semiaxes along the plane and in the $z$-direction, respectively. For completeness, Figures 3d and 4d show two runs similar to the ones displayed in Figures 3b and 4b for the face-on configuration, but allowing for shell fragmentation via the R-T instability. The evolutionary tracks are similar, except for a small increase in the expansion velocities for the cases allowing for the R-T instability.

The results presented in Figures 3 and 4 indicate that the expected expansion velocities for elongated bubbles in face-on galaxies are certainly larger than those derived from spherically symmetric models. The corresponding radii, however, are almost identical in both cases. A comparison of the results for small and large clouds (models A and B, respectively) show that the departures from the spherical case have well-defined trends. For instance, the maximum value of the expansion velocity for smaller clouds is reached much earlier than in the case of larger clouds. In addition, the velocity tracks for bubbles generated from small clouds are more peaked and can reach higher velocity values. Thus, as the cloud size increases, the peak velocity value decreases and the evolutionary track becomes shallower. In all flattened cloud cases, however, the expansion velocity remains well above that of the spherical model. For the particular cases that we show here, the expansion velocities can be higher than 20 km s$^{-1}$ during the first 3 Myr of evolution.

These results raise the obvious question of how one can distinguish between spherical and elongated objects in a face-on galaxy. The simplest way to resolve this issue is to look for differences in the velocity distribution as a function of the bubble radius. To make the results independent of any particular model, we define the impact parameter $a$ as the normalized distance from the bubble center. The normalization is done with the maximum shell radius, $r_{\text{max}}$ for the face-on configurations, and with the maximum $z$-extension, $a = z/Z_{\text{top}}$, for the edge-on cases. The $z$- and $r$-components of the expansion velocities are also normalized to the maximum projection velocity, $U_{\text{max}}$. The resulting velocity distributions for the A models are shown in Figure 5 (the results for the B models are qualitatively similar). The solid lines represent the spherical model A1, and the dotted and dashed lines correspond to the face-on and edge-on configurations of model A2, respectively. Figure 5a displays the velocity distribution after 2 Myr, and Figure 5b shows the same distribution after 1 Myr. At this time the elongated shell already has an hourglass form, but the distributions for spherically symmetric and elongated face-on objects remain similar. A clear difference appears in the maximum value for the edge-on objects, which shifts to locations away from the center (Fig. 5, dashed lines). The differences among the three cases are apparent only after 2 Myr, and the corresponding velocity distributions show distinctive features. The spherical case maintains its initial monotonic form, and the edge-on case remains peaked off center, but now the face-on case becomes double-valued in regions close to the edge of the shell. This second velocity component near the shell boundaries becomes the kinematic feature that can help us to
recognize the existence of elongated bubbles seen face-on. For completeness, Figure 6 displays isovelocity contours for model A2 at 1 and 2 Myr of evolution, and as seen in face-on and edge-on galaxies.

Finally, Figure 7 illustrates the evolution of the X-ray luminosity, $L_X$, for the three models A. The bubble densities and temperatures drop faster in the elongated cases, and the resulting luminosities have a more rapid drop-off (in addition, the smaller thermal evaporation rates in the top shell regions prevent increases in the $L_X$ values). The X-ray luminosity is stabilized as soon as the bubbles begin to expand in the external ISM. In contrast, the emission from the spherically symmetric case increases monotonically during the first 4 Myr of evolution. These differences are due to the differences in kinematical evolution, but the present results should considered only lower limits because there are other important effects that have not been included here. For instance, the peak $L_X$ values can increase if one includes clumps (e.g., Arthur & Henney 1996; Silich et al. 1996) inside the hot remnant (the form of the curve, however, remains the same). In addition, if one includes the presence of fragments in the stellar ejecta (Franco et al. 1993), the X-ray luminosity of the expanding shell is increased at each impact, and the light curve is modified accordingly. These issues require a more detailed study and will be explored further in the near future.

4. DISCUSSION AND CONCLUSIONS

In this paper we have presented a possible solution to the apparent discrepancy between the observed properties of some well-observed LMC shells with high velocities and the standard bubble model. Our present model assumes that these shells are driven by energy injection from massive OB stars. This is a reasonable assumption for small bubbles, but may not be true for all observed holes and shells. In particular, the largest and most energetic observed superbubbles could be ascribed to a different, nonstellar, origin (such as the collision of high-velocity clouds with the gaseous disk; e.g., Tenorio-Tagle et al. 1987; Santillán et al. 1999).

The issue at hand is the role of the parent GMC in the kinematic properties of young bubbles when viewed, as in the case of the LMC, at an almost face-on orientation. For simplicity, our two-dimensional numerical calculations consider the presence of flattened GMCs but do not include the $z$-gradient of the main gaseous disk. Nonetheless, the results already indicate that bubbles blowing out of these flattened clouds can reach a high degree of asymmetry on a short timescale (during the first million years of expansion), with $z$-velocities in the range of the observed high-velocity cases. This is in line with the semianalytical results for a sharp density contrast discussed by Oey & Smedley (1998), but a steep density gradient is not really required. We find that for moderate values of the GMC flatness, the expansion velocities at the top could easily exceed those expected from spherical models by a factor of 2 or more. This scheme then provides a possible explanation of the observed high-velocity cases, with $V_{exp} \geq 25$ km s$^{-1}$ and radii of several tens of parsecs (Rosado et al. 1981, 1982; Rosado 1986; Oey 1996b).

With respect to the resulting X-ray luminosities, the present version of the model cannot explain the X-ray excess that is often observed in high-velocity superbubbles (Chu & Mac Low 1990; Rosado et al. 1993). To explore this issue, it is necessary to consider the destruction of preexisting gas clumps (Arthur & Henney 1996; Silich et al. 1996), or to include the interaction of fragmented ejecta with the expanding shell (Franco et al. 1993). Each of these mechanisms can increase the value of $L_X$ during different moments of the evolution.

The remarkable difference in the velocity distributions as a function of impact parameter for face-on and edge-on galaxies, illustrated in Figure 5, indicates that one can differentiate elongated and spherical shells in both face-on and edge-on galaxies. Spectral line splitting at the periphery of nebular shells and off-center peak velocity values are indicators of elongated morphologies in the face-on and edge-on cases, respectively. Observational studies with adequate spatial resolution are needed to verify these predictions in nearby galaxies with different orientations.

This is the same type of model that is commonly applied to explain fast starburst-driven outflows in external galaxies (see the review by Heckman 1997), and we have only added the expected density structure at the initial stages of outflow evolution. Our results indicate that the presence of star-forming clouds produce asymmetries on short timescales, and shell projection effects are important when comparing
models with observed shells. Future studies that include the destructive effects of expanding H II regions (e.g., Franco, Shore, & Tenorio-Tagle 1994) and the reacceleration generated by individual supernova explosions (e.g., Tenorio-Tagle et al. 1991; Franco et al. 1991b; Arthur & Falle 1993; Arthur & Henney 1996) will certainly improve our understanding of the early phases of superbubble evolution.

It is a big pleasure to thank Sally Oey and Margarita Rosado for helpful discussions on LMC bubbles and shells, and Jane Arthur for useful comments. We also thank Elias Brinks, David Thilker, and Rene Walterbos for information on superbubble population of spirals and irregulars. Special thanks to Steve Shore and an anonymous referee for very useful suggestions that greatly improved the final version of this paper. J. F. acknowledges partial support from DGAPA-UNAM grant IN130698, CONACyT grants 400354-5-4843E and 400354-5-0639PE, and an R&D CRAY Research grant. S. A. S. acknowledges support from a Royal Society grant for joint projects with the former Soviet Union states, and the staff of IoA and RGO in Cambridge, where this study was initiated. He thanks the Instituto de Astronomia-UNAM for support, hospitality, and friendly assistance during his visit to Mexico.
REFERENCES

Arthur, J., & Falle, S. A. E. G. 1993, MNRAS, 341, L63
Arthur, J., & Henney, W. 1996, ApJ, 457, 752
Avedisova, V. S. 1972, Soviet Astron., 15, 708
Bisnovatyi-Kogan, G. S., & Blinnikov, S. I. 1982, Soviet Astron., 26, 530
Bisnovatyi-Kogan, G. S., & Silich, S. A. 1995, Rev. Mod. Phys., 67, 661
Boulesteix, J., Courtois, G., Laval, A., Monnet, G., & Petit, A. 1974, A&A, 37, 33
Brinks, E., & Bajaja, E. 1986, A&A, 169, 14
Brinks, E., & Walter, F. 1998, in The Magellanic Clouds and Other Dwarf Galaxies, ed. T. Richtler & J. Braun (Aachen: Shaken), 1
Chu, Y.-H., & Mac Low, M.-M. 1990, ApJ, 365, 510
Comeron, F. 1997, A&A, 326, 1195
Crampton, D. 1979, ApJ, 230, 717
davies, R. D., Elliot, K. H., & Meaburn, J. 1976, MNRAS, 81, 89
Ehlerova, S., Palous, J., Theis, Ch., & Hensler, G. 1997, A&A, 328, 121
Elmegreen, B. G., & Chiang, W. H. 1982, ApJ, 253, 666
Ferriere, K., Mac Low, M.-M., & Zweibel, E. 1991, ApJ, 375, 239
Franco, J., Ferrara, A., Różyczka, M., Tenorio-Tagle, G., & Cox, D. P. 1993, ApJ, 407, 100
Franco, J., Ferrini, F., Ferrara, A., & Barsella, B. 1991a, ApJ, 366, 443
Franco, J., Plewa, T., & Garcia-Segura, G. 1997, in Starburst Activity in Galaxies, ed. J. Franco, R. Terlevich, & A. Serrano (Rev. Mexicana Astron. Astrofísica. Conf. Ser. 6) (Mexico, D.F.: Inst. Astron., UNAM), 172
Franco, J., Shore, S. N., & Tenorio-Tagle, G. 1994, ApJ, 436, 795
Franco, J., Tenorio-Tagle, G., & Bodenheimer, P. 1989, Rev. Mexicana Astron. Astrofísica, 18, 65
——, 1990, ApJ, 349, 126
Franco, J., Tenorio-Tagle, G., Bodenheimer, P., & Różyczka, M. 1991b, PASP, 103, 803
Garcia-Segura, G., & Franco, J. 1996, ApJ, 469, 171
Garcia-Segura, G., & Mac Low, M.-M. 1995a, ApJ, 455, 145
——, 1995b, ApJ, 455, 160
Hartquist, T. W., Dyson, J. E., Pettini, M., & Smith, L. J. 1986, MNRAS, 221, 715
Heckman, T. 1997, in Starburst Activity in Galaxies, ed. J. Franco, R. Terlevich, & A. Serrano (Rev. Mexicana Astron. Astrofísica. Conf. Ser. 6) (Mexico, D.F.: Inst. Astron., UNAM), 156
Heiles, C. 1979, ApJ, 229, 533
Hindman, J. V. 1967, Australian J. Phys., 20, 147
Kontorovich, V. M., & Pimenov, S. F. 1997, Sol. Phys., 172, 93
Lozinskaya, T. A., & Sitnik, T. G. 1988, AZh Lett., 14, 240
Mac Low, M.-M., & McCray, R. 1988, ApJ, 324, 776
Mac Low, M.-M., McCray, R., & Norman, M. L. 1989, ApJ, 337, 141
Mashchenko, S., Thilker, D., & Braun, R. 1998, A&A, 343, 352
McCray, R., & Kafatos, M. 1987, ApJ, 317, 190
McCray, R. X., & Milton, J. A. 1966, Australian J. Phys., 19, 343
Meaburn, J. 1980, MNRAS, 192, 365
Moreno, E., Alfaro, E. J., & Franco, J. 1999, ApJ, in press
Oey, M. S. 1996a, ApJ, 465, 231
——, 1996b, ApJ, 467, 666
Oey, M. S., & Massey, P. 1995, ApJ, 452, 210
Oey, M. S., & Smedley, S. A. 1998, AJ, 116, 1263
Palouš, J. 1992, in Evolution of Interstellar Matter and Dynamics of Galaxies, ed. J. Palous, W. B. Burton, & P. O. Lindblad (Cambridge: Cambridge Univ. Press), 65
Pellet, A., Astier, N., Viale, A., Courtes, G., Maucherat, A., Monnet, G., & Simien, F. 1978, A&A, 33, 439
Pikel’ner, S. B. 1968, Astrophys. Lett., 2, 97
Rosado, M. 1986, A&A, 160, 211
Rosado, M., Georgelin, Y. P., Georgelin, Y. M., Laval, A., & Monnet, G. 1981, A&A, 97, 542
——, 1982, A&A, 115, 61
Rosado, M., Le Coarer, E., Laval, A., & Georgelin, Y. P. 1993, Rev. Mexicana Astron. Astrofísica, 27, 41
Saken, J. M., Shull, J. M., Garmany, C. D., Nichols-Bohlin, J., & Fesen, R. A. 1992, ApJ, 397, 537
Santillán, A., Franco, J., Martos, M., & Kim, J. 1999, ApJ, 515, 657
Silich, S. A. 1992, Ap&SS, 195, 317
Silich, S. A., Franco, J., Palous, J., & Tenorio-Tagle, G. 1996, ApJ, 468, 722
Silich, S. A., & Tenorio-Tagle, G. 1998, MNRAS, 299, 249
Sivan, J. P. 1977, Ph.D. thesis, Univ. Provence (France)
Suchkov, A. A., Balsara, D. S., Heckman, T. M., & Leitherer, C. 1994, ApJ, 430, 511
Tenorio-Tagle, G., & Bodenheimer, P. 1988, ARA&A, 26, 145
Tenorio-Tagle, G., Franco, J., Różyczka, M., & Bodenheimer, P. 1987, A&A, 179, 219
——, 1990, A&A, 237, 207
Tenorio-Tagle, G., Różyczka, M., Franco, J., & Bodenheimer, P. 1991, MNRAS, 251, 318
Thilker, D. A. 1998, in Interstellar Turbulence, ed. J. Franco & A. Carramiñana (Cambridge: Cambridge Univ. Press), 104
Thilker, D. A., Braun, R., & Walterbos, R. 1998, A&A, 332, 429
Tomisaka, K. 1990, ApJ, 361, 15
——, 1998, MNRAS, 298, 797
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377
Westerlund, B. E., & Mathewson, D. S. 1966, MNRAS, 131, 371