Revista Mexicana de Astronomía y Astrofísica, **29**, 91-96 (1994)

SINGLE AND MULTI-SUPERNOVA REMNANTS

José Franco
Instituto de Astronomía, Universidad Nacional Autónoma de México

RESUMEN

Explosiones de supernova de estrellas masivas ocurren dentro de burbujas preexistentes (producidas por supernovas anteriores o por la acción de varias estrellas en una asociación OB) y crean remanentes compuestos. Así, el material arrojado por la supernova no evoluciona en un medio de densidad constante sino en uno que ha sido modificado por la estructura de la burbuja. Aquí describimos las principales características de remanentes evolucionando en cavidades formadas por vientos estelares precursores o por explosiones de supernova anteriores.

ABSTRACT

Supernova explosions from massive stars occur inside pre-existing bubbles (produced either by the supernova precursor or by the action of several stars in an OB association) and create composite remnants. Thus, the supernova ejecta do not evolve into a constant-density medium but into one that has been modified by the bubble structure. Here we describe the main features of remnants evolving in the cavities caused by precursor stellar winds or by previous supernova explosions.

Key words: **ISM: BUBBLES – ISM: GENERAL– ISM: SUPERNOVA REMNANTS – SHOCK WAVES**

1. INTRODUCTION

Massive stars, with initial masses above 8 $M_\odot$, have significant mass loss during their evolution and they are the progenitors of type II and Ib supernovae. The pre-supernova activity injects large amounts of mechanical energy and disturbs the surrounding medium. Thus, the collective action of stars from OB associations represents a rich energy source which may be controlling the main properties of the general interstellar medium (e.g., Cox & Smith 1974; Salpeter 1976; McKee & Ostriker 1977; Weaver et al. 1977; Abbott 1982; Cioffi & Shull 1991; see review by Ostriker & McKee 1988). The strong mechanical energy input generates hot cavities and expanding shells, and the resulting wind-driven bubbles and supernova remnants (either from a single progenitor or from an entire association) are believed to generate most of the structuring observed in the gaseous disk (e.g., Reynolds & Ogden 1978, 1979; Cowie et al. 1979; Heiles 1979; McCray & Snow 1979). Cavities and expanding shells in the ambient H I gas have been detected around galactic WR stars and OB associations (e.g., Dubner et al. 1990; Cappa de Nicolau & Olano 1990; Niemela & Cappa de Nicolau 1991). All these structures, together with supershells (e.g., Heiles 1979, 1984), have been ascribed to the combined action of supernovae, stellar winds, and expanding H II regions, and seem to be common features in the Milky Way and external galaxies (see review by Tenorio-Tagle & Bodenheimer 1988; Deul 1988).

Direct evidence for the actual structuring generated by evolved massive stars includes optical shells surrounding massive stars in the Galaxy (e.g., Chu 1981; Chu et al. 1983; Lozinskaya 1988; Dufour 1989) and in the Magellanic Clouds (Rosado 1989; Le Coarer et al. 1993; Rosado et al. 1994), IR dust echoes from actual SN explosions (e.g., Dwek 1983), gas structures surrounding supernova remnants (e.g., Chevalier 1984; Fransson 1986; Braun & Strom 1987; Chevalier 1988), and interstellar features around young pulsars (Braun et al. 1989). The exciting stars include main sequence and Of or WR types, and indicate that the stellar activity is not restricted to particular evolutionary phases. In addition, recent optical studies suggest that the Crab Nebula is embedded within a bubble (Romani et al. 1990), and that SN 1987A is surrounded by a circumstellar structure (e.g., Crotts et al. 1989; Fransson et al. 1989; Wampler et al. 1990; Jakobsen et al. 1991).

The density structure in the neighborhood of supernova explosions, then, is expected to be fairly complex, and there is large number of studies devoted to exploring the details of the interaction between supernova (SN) ejecta and pre-existing shells. Here we review some of the main features of supernova remnant (SNR) evolution in these interstellar cavities and discuss the effects of ejecta fragmentation in the resulting remnant morphologies.

2. ANALYTICAL STUDIES

The studies of the evolution of remnants inside interstellar cavities began only in the early 80's, and the most important features of the analytical and 1-D studies have been recently reviewed by Franco et al. (1991, 1992). Here we give a brief summary of them. Ejecta thermalization defines the very first stages of the evolution, and occurs via a reverse shock (see Chevalier 1988). The details of this thermalization depends on the properties of both the expanding ejecta and ambient conditions. Early numerical models with constant density ejecta (e.g., Gull 1973) showed that thermalization is completed only after the main outgoing shock has swept-up an ambient gas mass in excess of about 40 to 50 times the ejected mass. The exact value is, of course, model dependent but this figure suggests that the required thermalization mass is non-negligible. Most studies of SNR evolution, however, did not consider this stage and simply assumed that the SN energy was already thermalized and driving a blast wave into the surrounding medium. When the explosion occurs inside a low-density cavity, thermalization is delayed until the outgoing shock encounters the outer shell. Under certain circumstances (i.e., due to strong radiative cooling in high density regions; e.g., Wheeler et al. 1980), the quasi-adiabatic Sedov-Taylor phase is missed. The initial cavity can be generated by a single star, via winds and photoionization (e.g., Weaver et al. 1977; McKee et al. 1984; McKee 1988), or by the combined effect of stellar winds and previous SN explosions.

Another important problem in the early stages of SNR evolution is the definition of a realistic structure for the expelled matter. Simple fits to the results of explosion models indicate that power-law stratifications represent adequate approximations to ejecta density and velocity profiles (e.g., see Woosley et al. 1988), and they have been widely used in analytical and numerical studies of remnant evolution. The self-similar solutions for an adiabatic blast wave were first described in the book by Sedov (1959). This book, which is one of the most comprehensive references on blast waves, includes solutions for adiabatic shocks evolving in power-law density distributions. For negative exponents, corresponding to increasing density gradients, Cox & Franco (1981) applied Sedov's solutions to shocks evolving in pre-existing cavities. They derived the energy and electron temperature distributions, and performed diagnostics for the expected luminosity, making Sedov's models available for SNR modelling (see further developments in Cox & Edgar 1983; Edgar & Cox 1984; Ostriker & McKee 1988; Ryu & Vishniac 1991). Chevalier (1982) and Nadyozhin (1985) derived solutions for the outgoing and reverse shocks assuming power-law distributions for both the ejecta and the ambient medium (particular self-similar solutions for the outgoing shocks were first derived by Parker 1963). More recently, Chevalier & Liang (1989) obtained analytical approximations for the interaction of power-law ejecta with the main features of a wind-driven cavity. Tenorio-Tagle et al. (1991) extended these approximations and followed the thermalization of the ejecta with the massive shell. The solutions described in these works provide an adequate reference frame to analyze, and test, the main features appearing in 1-D numerical models.

Some of these works focused on the evolution in decreasing ambient densities, which are expected in the innermost (free expanding wind) regions of wind-driven cavities (see also Cavaliere & Messina 1976). Negative density gradients result in shock acceleration (e.g., Sedov 1959; Ostriker & McKee 1988), and this acceleration becomes unbounded for power-laws with exponents greater than 3 (see approximations by Franco et al. 1990). A free expanding wind is characterized by $\rho \sim r^{-2}$, and there is a mild acceleration when the ejecta run through it (i.e., at the very first stages after explosion). One important feature of this accelerating phase is that the ejecta can become Rayleigh-Taylor unstable (see Falk & Arnett 1973; Chevalier 1976), and high-density fragments can be formed. This is an important aspect because there is growing observational evidence indicating that SN ejecta are not smooth plasma but in fact contain dense fragments. The best example of fragmented supernova ejecta interacting with the surrounding gas is found in Cas A (e.g., Braun et al. 1987 and references therein). There are also indications of a possible fragmentation in Puppis A (Winkler et al. 1988) and in some other objects (e.g., Hamilton 1985; Braun 1988; Danziger & Bouchet 1989), including SN 1987A (see Arnett et al. 1989 and Lucy et al. 1989). The effects generated by the resulting fragments depend on their size and ambient conditions. Hamilton (1985) derived similarity solutions for power-law stratifications in both clump distribution and ambient density. Obviously, the higher density fragments can move ahead of the shock front and they generate precursor bow shocks. When located in a cavity, these fragments move almost unimpeded inside the bubble, but they are rapidly thermalized at impact with the external shell. These interactions drive strong shocks at the places of impact, generating a variety of time-dependent features and can even puncture the original shell (Tenorio-Tagle et al. 1991; Franco et al. 1993). Similar effects are produced when a clump of ejecta interacts with ambient clouds (McKee 1983).

3. NUMERICAL STUDIES

3.1. 1-D Models

Numerical simulations represent a powerful tool to follow the details of the evolution inside bubbles. Assuming spherically symmetric flows, most studies have been performed with one-dimensional hydrodynamical codes. Fabian et al. (1983); Itoh & Fabian (1984); Dickel & Jones (1985); Shull et al. (1985); Band & Liang (1988); Ciotti & D'Ercole (1988); Tenorio-Tagle et al. (1988) followed the ejecta interaction through a bubble. The interaction of the outgoing shock with the shell produce soft X-rays and optical emission, and thus the remnant becomes observable only when it reaches the outer shell. Another interesting feature coming out of these studies is the appearance of a series of new shock waves, both refracted and reflected, as the flow adjusts to the density variations.

Tenorio-Tagle et al. (1990) performed detailed 1-D simulations, with high spatial resolution, and confirmed most of the previous analytical and numerical results. These models display a large variety of details generated by the refracted and reflected shocks (the lifetime of these multiple-shock patterns, and the importance of the associated effects, is severely reduced when one includes non-radial motions). In addition, for shell masses larger than about 50 times the mass of the ejecta (which is coincidental with the thermalization mass obtained by Gull 1973), radiative losses dominate the interaction and there is no adiabatic phase (similar to a SN exploding inside a molecular cloud; e.g., Shull 1980; Wheeler et al. 1980). The remnant shines in the visible much earlier and ages much faster than its constant density counterparts. For less massive shells, there is also a strong optical emission generated at the moment of interaction, but only a small fraction of the energy is lost in radiation. In this case, the leading shock overruns the shell creating a complex multi-shell structure. In all 1-D cases, however, the ejecta and the ambient matter remain well separated and stratified. This flow stratification is simply due to the assumed spherical symmetry, which prevents the development of flow instabilities and lateral mixing.

3.2. 2-D and 3-D Models

Two-dimensional hydrodynamical codes have been used in studies of both single and multiple SN exploding inside pre-existing bubbles (see reviews by Tenorio-Tagle & Bodenheimer 1988; Franco et al. 1992). These codes have a lower spatial resolution than 1-D models, but allow detailed simulations with complex initial conditions, including the motion of the progenitor star and fragmented and unfragmented ejecta. The results of these models display a rich variety of new effects, and indicate that many "strange" morphological features of actual remnants could be ascribed to either progenitor motions or uneven ambient and ejecta conditions (or both).

For cases with static progenitors and unfragmented ejecta, the 2-D models for single remnants reproduce most of the results from 1-D simulations except that no stratification is maintained (see Tenorio-Tagle et al. 1990). The ejecta expand almost unimpeded within the bubble and undergo a fast thermalization at interaction with the shell. The dimensions of the resulting remnants, then, are basically determined by the size of the pre-existing cavity. Depending on the shell mass, radiative cooling can be very efficient and the Sedov-Taylor phase can be inhibited. Thus, no simple evolutionary tracks can be applicable to actual remnants. After the re-accelerated shell has cooled down, the remnant is deformed by thermal and Rayleigh-Taylor instabilities. Also, when the explosion occurs near the edge of the massive shell (or near the edge of a molecular cloud), the density gradient can accelerate the cooling gas and fast H_α (and other recombination lines) emission is produced (Arthur & Falle 1993). Finally, the additional degree of freedom in 2-D models allows for lateral motions and a series of chaotic velocity fields, with rotating eddies, are created inside the remnant. These turbulent motions mix different gas components and destroy the multiple-shock pattern displayed by 1-D models. Also, unstable modes are no longer quenched by the enforced symmetry of the flow, and thermal and Rayleigh-Taylor instabilities develop in the cooling shell.

When the progenitor star is moving with respect to the ambient medium, the wind driven shell gets distorted and the explosion occurs off-center (Różyczka et al. 1993; Brighenti & D'Ercole 1993). Depending on the star velocity, the wind cavities can be highly elongated and the explosions can occur near the edge of the cavity. As stated before, this extreme case generates fast H_α emission but also produces highly distorted remnants, with two lobes. The distortion decreases with decreasing velocities and the second lobe disappears for moderate velocities. The SN shock first hits the leading part of the pre-existing shell and, due to strong radiative cooling, the excited part of the remnant looks like a bright arc-like feature. Later on, as the shock reaches the res of the shell, the arc extends to fill the whole shell but the initial arc fades out with time. Given that a larg section of the shell is processed by an oblique shock, the shocked gas can flow parallel to the shell and induc Kelvin-Helmholtz instabilities. These instabilities provide some mass transfer from the shell to the cavity, an generate further distortions in the composite remnant (i.e., the remnant becomes elongated and corrugated) Also, given the delays in shock arrival to different sections of the shell, a multitude of shock reflections wit different strengths and directions cause a very complex flow which is absent in the previously explored scenarios

In the case of multi-supernova remnants, after the first analytical formulation by Bruhweiler et al. 1980 a large number of numerical simulations (covering a wide range of ambient conditions) have appeared (e.g. Tomisaka et al. 1981; Tomisaka & Ikeuchi 1986; McCray & Kafatos 1987; Tenorio-Tagle et al. 1987; Mac Low & McCray 1988; Igumentshchev et al. 1990; Palouš et al. 1990; Tenorio-Tagle et al. 1990; Ferriere et al.1991 Silich et al. 1993). These simulations have been performed with a pulsed mass and energy input (to simulat the injection from repeated explosions), and include the disk density stratification along the z-axis and, in a few cases, an external B-field or the galactic differential rotation. The models show the formation of a ric variety of gaseous structures associated with flow instabilities in cooling shocks, accelerations due to decreasin density gradients, or to the shear generated by galactic rotation (see reviews by McCray 1988, Tenorio-Tagl & Bodenheimer 1988, Różyczka 1989, and Franco et al. 1992). Some of the most recent works, in 3-D, als include the effects of a clumpy interstellar medium and derive, aside from the flow variables, the evolution o the X-ray emission and the distorted 3-D shape of a sheared remnant (Silich et al. 1993).

The cases with fragmented ejecta contain a series of new time-dependent effects and a variety of localize and transient features. The importance of these features depends on the assumed fragment sizes and densities In the first approach to the problem, Hamilton (1985) considered the case of ejecta composed of clumps onl and assumed that their properties were stratified as a power-law with radial location in the ejecta (i.e., th denser and smaller clumps were located in the innermost parts). One of the most important results of thi study is that SNRs driven by clumpy ejecta can have precursors moving ahead of the main shock front. Thi result is confirmed with numerical simulations in which the fragments have density enhancements with respec to the rest of the "inter-fragment" medium (Tenorio-Tagle et al. 1991). When evolving in a bubble interior, th fragmented ejecta has a similar behavior as in the cases described before, except that the fragments are eve less affected than the inter-fragment medium. Fragment thermalization occurs at impact with the shell, but th energy and momentum rates injected by the fragments are larger. Thus, stronger shocks are generated whic heat and accelerate the shell gas at the particular places of impact. The remnant interior generates a chaoti velocity field, and gas mixing is more efficient than in the unfragmented case. When the ambient medium i very dense, the shocked fragments cool down very quickly and undergo fast thermal instabilities (Różyczk et al. 1994). In the case of large multi-supernova remnants, the collisions can puncture the shell during the firs million years of superbubble evolution (Franco et al. 1993). Thus, fragmented, or clumpy, ejecta have a stron impact on the structure and appearance of both single and multi-SNR.

In summary, the interaction of the ejecta with a pre-existing shell generates optical and X-ray emission creates a multi-shell structure, and re-accelerates the former shell. The early radiative phase may be responsibl for the optical and X-ray emission of many galactic remnants and, for large radiative losses, may drive th evolution directly into the momentum conserving stage. If the ejecta contain high-density fragments, they ca puncture the shell and enhance the early emission. If the progenitor star moves with respect to the ambien gas, the resulting shell is heavily distorted and may be composed of at least two lobes. Thus, a combination o wind-driven shells with fragmented ejecta and progenitor motions could account for the wide variety of observe remnant emission features and morphologies.

Most of the work described here was performed over several years with my good friends and collaborator P. Bodenheimer, D. Cox, A. Ferrara, J. Palouš, M. Różyczka, S. Silich, G. Tenorio-Tagle, and R. Terlevich This work was partially supported by DGAPA-UNAM through grant IN103991, and several of the simulation described in this work were performed with the CRAY/YMP of the UNAM Supercomputing Center.

REFERENCES

Abbott, D.C. 1982, ApJ, 263, 723

Arnett, D., Fryxell, B., & Müller, E. 1989, ApJ, 341, L63

Arthur, S.J., & Falle, S.A.E.G. 1993, MNRAS, 261, 681

Band, D.L., & Liang, E. P. 1988, in Supernova Remnants and the Interstellar Medium, IAU Coll. 101, ed. R.S Roger & T.L. Landecker (Cambridge: Cambridge U. Press), p. 69

Braun, R. 1988, in Supernova Remnants and the Interstellar Medium, IAU Coll. 101, ed. R.S. Roger & T.L. Landecker (Cambridge U. Press), p. 227
Braun, R., Goss, W.M., & Lyne, A.G. 1989, ApJ, 340, 355
Braun, R., Gull, S.F., & Perley, R. 1987, Nature, 327, 395
Braun, R., & Strom, R.G. 1987, A&A, 164, 193
Brighenti, F., & D'Ercole, A. 1993, Numerical Simulations in Astrophysics, ed. J. Franco, L. Aguilar, S. Lizano, & E. Daltabuit, (Cambridge: Cambridge U. Press), in press.
Bruhweiler, F.C., Gull, T., Kafatos, M., & Sofia, S. 1980, ApJ, 238, L27
Cappa de Nicolau, C., & Olano, C.A. 1990, RevMexAA, 21, 269
Cavaliere, A., & Messina, A. 1976, ApJ, 209, 424
Chevalier, R.A. 1976, ApJ, 207, 872
______. 1982, ApJ, 258, 790
______. 1984, Ann. NY Acad. Sci., 422, 215
______. 1988, in Supernova Remnants and the Interstellar Medium, IAU Coll. 101, ed. R.S. Roger & T.L. Landecker (Cambridge U. Press), p. 31
Chevalier, R.A., & Liang, E.P. 1989, ApJ, 344, 332
Chu, Y.-H. 1981, ApJ, 249, 195
Chu, Y.-H, Treffers, R.R., & Kwitter, K.B. 1983, ApJS, 53, 937
Cioffi, D.E., & Shull, J.M. 1991, ApJ, 367, 96
Ciotti, L., & D'Ercole, A. 1988, A&A,215, 347
Cowie, L.L., Songaila, A., & York, D.G. 1979, ApJ, 230, 469
Cox, D.P., & Edgar, R. 1983, ApJ, 265, 443
Cox, D.P., & Franco, J. 1981, ApJ, 251, 687
Cox, D.P., & Smith, B.W. 1974, ApJ, 189, L105
Crotts, A.P.S., Kunkel, W.E., & McCarthy, P.J. 1989, ApJ, 347, L61
Danziger, I.J., & Bouchet, P. 1989, in Evolutionary Phenomena in Galaxies, ed. B. Pagel & J. Beckman (Cambridge U. Press), p. 283
Deul, E. 1988, Ph.D. Thesis, Leiden, The Netherlands.
Dickel, J.R., & Jones, E.M. 1985, ApJ, 288, 707
Dubner, G.M., Niemela, V.S., & Purton, C. 1990, AJ, 99, 857
Dufour, R.J. 1989, RevMexAA, 18, 87
Dwek, E. 1983, ApJ, 274, 175
Edgar, R.J., & Cox, D. P. 1984, ApJ, 283, 883
Fabian, A.C., Brinkman, W. & Stewart, G.C. 1983, in Supernova Remnants and Their X-ray Emission, IAU Symp. 101, ed. J. Danziger & P. Gorenstein (Dordrecht: Reidel), p. 119
Falk, S.W., & Arnett, D. 1973, ApJ, 180, L65
Ferriere, K.M., Mac Low, M.M., & Zweibel, E. 1991, ApJ, 375, 239
Franco, J., Bodenheimer, P., Tenorio-Tagle, G., & Różyczka, M. 1992, Evolution of Interstellar Matter and Dynamics of Galaxies, ed. J. Palouš, W. Burton, & P. Linblad, (Cambridge: Cambridge U. Press), p. 130
Franco, J., Ferrara, A., Różyczka, M., Tenorio-Tagle, G., & Cox, D. 1993, ApJ, 407, 100
Franco, J., Tenorio-Tagle, G. & Bodenheimer, P. 1990, ApJ, 349, 126
Franco, J., Tenorio-Tagle, G., Bodenheimer, P. & Różyczka, M. 1991, PASP, 103, 803
Fransson, C. 1986, in Radiation Hydrodynamics in Stars and Compact Objects, ed. D. Mihalas & K.H. Winkler (Springer: Berlin), p. 141
Fransson, C., Cassatella, A., Gilmozzi, R., Kirshner, R.P., Panagia, N., Sonnerborn, G. & Wamsteker, W. 1989, ApJ, 336, 429
Gull, S.F. 1973, MNRAS, 161, 47
Hamilton, A.J.S. 1985, ApJ, 291, 523
Heiles, C. 1979, ApJ, 229, 533
______. 1984, ApJS, 55, 585
Itoh, H., & Fabian, A.C. 1984, MNRAS, 208, 645
Igumentshchev, I.V., Shustov, B.M., & Tutukov, A.V. 1990, A&A, 234, 396
Jakobsen, P. et al. 1991, ApJ, 369, L63
Le Coarer, E., Rosado, M., Geogelin, Y.P., et al. 1993, A&A, 280, 365
Lozinskaya, T.A. 1988, in Supernova Remnants and the Interstellar Medium, IAU Coll. 101, ed. R.S. Roger & T.L. Landecker (Cambridge: Cambridge U. Press), p. 95
Lucy, L.B., Danziger, I.J., Gouiffes, C., Bouchet, P. 1989, in Structure and Dynamics of the Interstellar Medium,

IAU Coll. 120, ed. G. Tenorio-Tagle, M. Moles, & J. Melnick (Springer: Berlin), p. 164
Mac Low, M.M., & McCray, R. 1988, ApJ, 324, 776
McCray, R., & Snow, T.P. Jr. 1979, ARA&A, 17, 213
McCray, R. 1988, in Supernova Remnants and the ISM, IAU Coll. 101, ed. R.S. Roger & T.L. Landecker (Cambridge: Cambridge U. Press), p. 447
McCray, R., & Kafatos, M. 1987, ApJ, 317, 190
McKee, C.F. 1983, in Supernova Remnants and their X-ray Emission, IAU Symp. 101, ed. J. Danziger & P. Gorenstein (Dordrecht: Reidel), p. 87
______. 1988, in Supernova Remnants and the ISM, IAU Coll. 101, ed. R.S. Roger & T.L. Landecker (Cambridge: Cambridge U. Press), p. 205
McKee, C.F., van Buren, D., & Lazareff, B. 1984, ApJ, 278, L115
McKee, C. F. & Ostriker, J. P. 1977, ApJ, 218, 148
Nadyozhin, D.K. 1985, Ap&SS, 112, 225
Niemela, V.S. & Cappa de Nicolau, C. 1991, AJ, 101, 572
Ostriker, J.P. & McKee, C.F. 1988, Rev. Mod. Phys., 60, 1
Parker, E.N. 1963, Interplanetary Dynamical Processes, (New York: Interscience)
Palouš, J., Franco, J., & Tenorio-Tagle, G. 1990, A&A, 227, 175
Reynolds, R.J., & Ogden, P.M. 1978, ApJ, 224, 94
______. 1979, ApJ, 229, 942
Romani, R.W., Reach, W.T., Koo, B.C., & Heiles, C. 1990, ApJ, 349, L51
Rosado, M. 1989, RevMexAA, 18, 105
Rosado, M., Le Coarer, E., & Georgelin, Y.P. 1994, A&A, in press
Różyczka, M. 1985, A&A, 143, 59
______. 1989, in Structure and Dynamics of the ISM, ed. G. Tenorio-Tagle, M. Moles, & J. Melnick, (Springer: Berlin), 463
Różyczka, M., Tenorio-Tagle, G., Franco, J., & Bodenheimer, P. 1993, MNRAS, 261, 674
Różyczka, M., Franco, J., Miller, W., Tenorio-Tagle, G., & Terlevich, R. 1994, in preparation
Ryu, D., & Vishniac, E.T. 1991, ApJ, 368, 411
Salpeter, E.E. 1976, ApJ, 229, 533
Sedov, L.I. 1959, Similarity Solutions and Dimensional Methods in Mechanics, (New York: Academic Press)
Shull, J.M. 1980, ApJ, 237, 709
Shull, P. Jr, Dyson, J.E., Kahn, F.D., & West, K.A. 1985, MNRAS, 212, 799
Silich, S., Franco, J., Tenorio-Tagle, G., & Palouš, J. 1993, Numerical Simulations in Astrophysics, ed. J. Franco, L. Aguilar, S. Lizano, & E. Daltabuit, (Cambridge: Cambridge U. Press), in press
Tenorio-Tagle, G., Bodenheimer, P., & Różyczka, M. 1987, A&A, 182, 120
Tenorio-Tagle, G., & Bodenheimer, P. 1988. ARA&A, 26, 145
Tenorio-Tagle, G., Bodenheimer, P., & Franco, J. 1988, in High Energy Astrophysics, ed. G. Börner, p. 77
Tenorio-Tagle, G., Bodenheimer, P., Franco, J., & Różyczka, M. 1990, MNRAS, 244, 563
Tenorio-Tagle, G., Różyczka, M., Franco, J., & Bodenheimer, P. 1991, MNRAS, 251, 318
Terlevich, R., Tenorio-Tagle, G., Franco, J., & Melnick, J. 1991, MNRAS, 255, 713
Tomisaka, K., Habe, H., & Ikeuchi, S. 1981, Ap&SS, 78, 273.
Tomisaka, K., & Ikeuchi, S. 1986, PASJ, 38, 697
Wampler, E.J., Wang, L., Baade, D., Banse, K., D'odorico, S., Gouiffes, C., & Tarenghi, M. 1990, ApJ, 362, L13
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377
Wheeler, J.C., Mazurek, T.J., & Sivaramakrishnan, L. 1980, ApJ, 237, 781
Winkler, P.F., Tuttle, J.H., Kirshner, R.P. & Irwin, M.J. 1988, in Supernova Remnants and the Interstellar Medium, IAU Coll. 101, ed. R.S. Roger & T.L. Landecker (Cambridge: Cambridge U. Press), p. 65
Woosley, S.E., Pinto, P.A., & Ensman, L. 1988, ApJ, 324, 466

J. Franco: Instituto de Astronomía, UNAM, Apdo. Postal 70-264, 04510 México, D.F., México. e-mail: pepe@astroscu.unam.mx.