Guide to Modeling the Interstellar Medium

DONALD P. COX

University of Wisconsin-Madison, Dept. of Physics,
1150 University Avenue, Madison, WI 53706 USA

We are in a period that is rich with data and ideas, but the collection of ideas is fundamentally incomplete, leaving us with no useful model for the general characteristics of the interstellar medium (Cox 1995). At the same time, we wrestle with tentative models at various levels, and concepts that such synthesis modeling must involve. In the list and commentary that comprise this paper I offer to future explorers what limited wisdom I can.

Heating-Cooling Balance: It is not clear that the heating of interstellar clouds is sufficiently well understood, but what is clear is that at densities above 10 cm^{-3}, thermal equilibration can be regarded as rapid. The temperature is effectively just a function of the density, as is the thermal pressure. At densities of order 0.1 cm^{-3}, impulsively heated gas will fairly rapidly drop to 10^4K, but below that there is a long slow transient. Even so, the slogan "the gas cools before it recombines" from the days of stochastic heating models (from assumed SNe radiations) is still apropos. Warm intercloud gas is likely often out of thermal balance, and even more often out of ionization equilibrium.

Interphase Pressure Balance: It has often been suggested that contiguous regions of very different density should have about equal thermal pressures. Unless we have been badly deceived, however, the Local Bubble surrounding the Local Cloud (or wisp, if you prefer) has more than an order of magnitude higher thermal pressure than the cloud (e.g., Bowyer et al. 1995). For those comfortable with magnetic fields, this poses no great problem, one merely supposes that the typical magnetic pressure of the ISM is absent from the very low density hot bubble. There is still rough total pressure balance, the thermal pressure of the hot gas against the magnetic pressure in the wisp. A few microgauss is sufficient, tangent to the wisp surface. This tangent field also helps keep the wisp from evaporating into the hot gas—without such help it should long ago have disappeared (Cox & Reynolds 1987).

Interphase pressure balance is still a useful concept, but it must be employed somewhat cautiously—including magnetic field pressure and tension (more on this later). By and large, thermal pressure appears to be relatively small except in hot low density regions. In cooler regions, one can perhaps think of the surrounding magnetic field pressure as providing an upper limit to the contained thermal pressure. For short distances along flux tubes, thermal pressure should be relatively uniform, but needn't equal that of the surroundings. In addition, the absence of a significant bulk modulus associated with the thermal pressure at typical cloud parameters could lead to some very interesting effects reminiscent of critical point opalescence (Cox 1988).

Hydrostatics: The vertical structure of the Galaxy is far from static, but it is close enough to stationary that the midplane pressure is essentially the weight of the interstellar matter. One has only to be a little careful in defining pressure, to be certain that it contains all relevant forms. Boulares & Cox (1990) found the total weight of the interstellar matter to have $p/k{\sim}25{,}000$ cm^{-3} K, divided about equally between dynamic, cosmic ray, and magnetic forms. Unless there is an extensive hot phase at high thermal pressure (see below),volume averaged thermal pressure is negligible.

Hydrostatics in the ISM is a bit more complicated than on Earth, however; the weight

S. Bowyer and R. F. Malina (eds.), Astrophysics in the Extreme Ultraviolet, 247–254.

depends not only on the mass per unit area, but also on the vertical distribution, because gravity does.

As a consequence, vertical models of the ISM must look either for reasons why the mass has the vertical distribution it does—what specifies the scale heights of the various components, or for reasons why the structure has the midplane pressure it does. In the two phase model of Field, Goldsmith, & Habing (1969), only intercloud gas was stable at low pressure and formed an atmosphere. Because there was more than enough matter, the lower reaches of that atmosphere had sufficient thermal pressure to confine stable clouds. These low lying clouds contained much of the mass but had little weight. Thus the thermal pressure adjusted itself to make the clouds stable. In the McKee & Ostriker (1977) model, supernova remnants grew to very large sizes in a low intercloud density environment, the average pressure of the medium being roughly the time and volume averaged energy density. Those two different models found two totally different reasons for the ISM to have about the pressure it does.

My sense is that the pressure problem is badly overdetermined and that we are missing some vital links. Although the FGH model is not valid in detail, there are similar two phase models based on photoelectric rather than cosmic ray heating (e.g., Wolfire, Hollenbach, McKee, Tielens & Bakes 1995) that lead to predictions of the thermal pressure required within stable clouds. One might suppose that the medium, via a mechanism like that sketched in FGH, conspires to stabilize clouds to avoid having too dense an intercloud medium. But the situation is precarious. For example, if the atmosphere of the Earth were removed, and if the oceans were pure water, water would evaporate to create an atmosphere sufficient to prevent the oceans' further boiling. Only the top few meters of ocean would be required. But the ISM is very different. Roughly half the mass is in molecular clouds, the other half split fairly evenly between the diffuse clouds and the warm intercloud medium—there is not a huge reservoir of evaporable material in the clouds.

But that's only half the problem. I can't shake the feeling that McKee & Ostriker were correct in their notion that the SNR pressure is important. Some of the energy is distributed very widely and is not fully dissipated for a long time. The lower the pressure of the surroundings, the larger the region perturbed and the longer it lasts, raising the remnant contribution to the pressure. Let us suppose we could formulate a theory that would determine the SNR contribution to the pressure as a function of the intercloud density, the SN rate per unit volume, and the total pressure. Plug in the observed values and bingo, we find out what the remnants can accomplish. I have done this more than once over the years, essentially always with the same result, $p/k \sim 10^4$ cm^{-3} K. Maybe I got that result because I wanted it, or maybe because it is unavoidable. In any case it is very strange. It is a sufficient pressure to bind the clouds. But in today's models, the pressure required to bind diffuse clouds depends on gas metallicity, depletion onto grains, details of the properties of very small grains, and the abundance of starlight. Why do both pressure estimates, depending on totally different quantities and physics, concur to within better than a factor of 3? Which is in control? Are dust grains modified in the intercloud environment until they have properties that will admit stable clouds in the pressure defined by the supernovae? Is the supernova rate controlled by the interstellar pressure, so that cloud existence is accomplished via adjustment of the SNR pressure, and only secondarily through the associated adjustment of the weight of the intercloud gas?

Or is something altogether different "in charge"? For example, somewhere I heard that cold disks are unstable, buckling and heating themselves spontaneously to achieve an acceptable scale height. I have wondered whether this might happen to the interstellar component as well as to the stars. If it does, then one presumes that a certain minimum interstellar pressure is required by the disk itself. Much of this pressure could be ballistic, but my sense is that the ISM cannot consist of ballistic bits as the stars do—more on that below. Maybe in many regions, this disk stabilization pressure is all there is. If there is too little surface density of interstellar material, it will all be in intercloud form, with no star formation, and no supernovae. With more material, some will be able to condense, leaving clouds, stars, supernovae, dust, and starlight in the right relative proportions to make things behave the way they do in our vicinity. Perhaps with even more interstellar matter, the supernovae become important contributors to the pressure and the disk inflates beyond the disk-required thickness. Perhaps star formation enters a runaway mode, a starburst with its own controls, until the gaseous surface density drops to a more quiescent level. In short, perhaps the Galaxy has the gaseous surface density it does because if it had more it would rapidly dump it into stars. So we sit just below a critical surface density with all sorts of odd coincidences baffling us. At a lower surface density yet, one supposes we wouldn't be here to wonder why.

Dynamic Pressure: Spitzer told us that the mean free path between clouds is 160 pc and that at a mean speed of $\sim$10 km s^{-1} $\sim$10 pc Myr^{-1} they would collide every 20 Myr or so. That was long ago and I don't know whether he would say it now, but it probably isn't a very accurate picture. Clouds are not isolated entities, they are probably structures within structures, interacting over considerable distances via their connecting magnetic fields. You really want a model? How about the modern (and American) version of plum pudding? String some beads of lead shot on fishing line and suspend many such strings in rapidly cooling Jell-o. When jelling is complete, shake it. Notice that the lead shot moves around but there are never contact collisions. The motion of the Jell-o and shot is a form of dynamic pressure.

Turbulence: Turbulence doesn't mean what I think it should, not anymore. I don't like the word, but it has become a fixture and there's not much I can do about it; mathematically inclined plasma physicists got there first. Turb, turbine, twist, torque, eddy, swirl, twirl, turn. Apparently turbulence hasn't to do exclusively with these familiar forms. For example, I wouldn't be inclined to say that Jell-o could contain turbulence. Not unless I put it in a blender anyway. But its chief characteristic is a healthy wave field, and if through nonlinearities that wave field can cascade to shorter scales, then nowadays it's turbulence. So, my only words of wisdom on this subject are that when others speak of interstellar turbulence, cascades, power spectra and the like, do not immediately assume they are speaking of an eddy field.

Radiation Pressure: Radiation pressure is not always negligible. You'd be surprised how large it can be sometimes—take a look at articles on levitation of dust grains and interstellar material from Ferrini, Franco, & Ferrara, for example, or work it out for yourself. Do you really think it's an accident that the galactic disk has roughly optical depth unity and 1 eV cm^{-3} of starlight?

Cosmic Ray Pressure: There are people who believe that cosmic rays are accelerated by shock waves in supernova remnants. The initial surge of excitement came from discovery of the fact that a shock with the unique adiabatic compression factor of 4 would accelerate particles to the observed power law spectral index. Pre-radiative supernovae are a copious supplier of such shocks; because supernovae (with a reasonable available power) had long been suspected as the source, the leap was made. Last year, Don Ellison and Steve Reynolds made an extremely responsible attempt to bring together people who study SNRs and those who model cosmic ray acceleration. A very fine review appears in PASP (1994). My reaction (not widely shared among the participants) is that there is no more evidence that SNRs are the primary source of cosmic rays than there was say 25 years ago. (The synchrotron emission at the outer shocks of older remnants is insufficient evidence before correction for the Van der Laan mechanism.)

Nevertheless, cosmic ray acceleration, propagation, pressure, and escape from the Galaxy are all vital components of interstellar activity. You'd best not leave them out of your model. Does the rate of star formation depend on the population of cosmic rays that penetrate dense clouds and drive the ion chemistry there?

Magnetic Field Pressure, Tension, and Flux Ropes: It is easy to be uncomfortable with magnetic fields, or with the uses they are put to by modelers who seem to need the field to save their theories. But it is folly to pursue a model very far without inquiring whether the magnetic field expected to be present will not totally change the basic features. Even the most rudimentary inclusion is better than neglect. In the ISM, the magnetic field is one of the major pressure components, is difficult to compress but highly elastic, and has a major effect on transport processes—of the wave field, thermal conduction, and cosmic ray propagation in particular.

A striking feature of the field is that it pushes in two directions and pulls in the third. In force free configurations (e.g., the field around a current carrying wire or of a dipole), these two features are balanced. Tension provides a negative pressure, $-B^2/8\pi$, acting to straighten flux tubes, propagate transverse Alfven waves, drive the interchange instability, support clouds against the galactic gravity (Cox 1988; Boulares & Cox 1990), etc. The gradient of the tension provides net force even when the field lines are straight. The tension in twisted flux tubes supports torsional Alfven waves, and therefore transmission of torque.

Twisted flux tubes also pinch, and can conceivably be a major player in the mass transfer from low to high density. Because the field is strong and difficult to compress, intercloud material must normally be gathered along field lines or collect in reconnection regions (to rid itself of excess flux) to move to higher density. But the field can be used to overwhelm itself if it can be twisted. With sufficient torque, material can be squeezed in a flux rope much like water in a damp twisted towel. If ambipolar diffusion and/or reconnection is faster in this denser environment, a net transfer to higher density is achieved, even with the relaxation of the torque. Perhaps clouds drip out of the twisted towel.

I expect flux ropes to be common features in MHD models of spiral density waves, essentially because rolling motions will be unavoidable when the vertical structure of the waves is fully explored (Martos 1993). The waves are likely to resemble tidal bores more than simple shocks. (Tidal bores are hydraulic jumps; look for one in the floor of your kitchen sink next time you turn on the water.)

Flux ropes also provide one hope for understanding the presence of extremely dense interstellar material as a common feature (see e.g., Frail et al. 1994). We need to know, however, whether their formation requires extraordinary conditions or is a natural consequence of instabilities in already well accepted interstellar behaviors.

Note: I think it's an established fact that mass in the ISM tends to be concentrated at the largest scales—but if you start working on hierarchical models, you'd best check up on this.

Sheets and Shells: They exist, apparently, and are a major organizing feature of the mass distribution in the ISM (e.g., Bregman & Ashe 1991). Spectrally identifiable clouds are likely subunits within these larger structures. Presumably the structures arise via SN and superbubble activity.

Superbubbles, Chimneys, and Worms: These are easily confused concepts. Superbubbles are two things, large roundish structures observed in space and velocity, and the theoretical structures produced in models of the activity of OB associations. Chimneys are the nearly vertical walls of model superbubbles large enough to experience the density gradient normal to the galactic plane. Worms, on the other hand, are observed vertical structures containing an unknown fraction of the high z neutral hydrogen, that may or may not be related to the theoretical concept of chimneys. Opinion varies on whether it takes one or two worms to make a chimney. In one instance (Maciejewski et al. 1995) two worms appear to open into a V which is topped by an apparent superbubble $\sim$400 pc in diameter, extending about 600 pc off the plane.

In the past it has been fairly common to suppose that OB associations spewed effluent hot gas out into the galactic halo through their chimneys. That, however was prior to full appreciation of the vertical extent of the interstellar mass and field distribution (e.g., Cox 1989). At present it seems to be more fashionable to include the mass and pressure distribution as a uniform layer in which the chimneys of the largest OB associations blow large bubbles (e.g., Ferrière 1995), rather like the observed bubble described above.

Porosity: Porosity is a theoretical measure of the degree to which supernovae (or generalized to OB association bubbles) will disrupt a hypothetical ambient interstellar medium. It is a characteristic of a model. Specifically, for a given ISM model and SNR evolution within it, one calculates the volume fraction occupied by the population of remnants under the assumption that they do not overlap or interact.

If the result is not small compared to 1, one concludes that the remnants would disrupt the assumed medium and force it into an entirely different state in which hot gas and low density play a prominent part. McKee & Ostriker (1977) found that the porosity of a medium with warm intercloud density less than 0.3 cm^{-3} was at least 3. The calculation seemed simple, the logic unassailable. This result, which I took to calling the porosity imperative, was the one of three major motivations behind a broad acceptance of the idea that most of interstellar space was hot.

Slavin & Cox (1993), however, have shown that with current parameters and inclusion of nonthermal pressure, the porosity of a warm intercloud model could be less that 0.1. Our results do not guarantee that the supernovae would not disrupt the medium, but the porosity imperative has lost its oomph. Things are no longer so clear, though they certainly would be if Slavin's remnants were observed with their predicted characteristics in the FUV.

Hot Gas in the ISM: We have discussed this elsewhere at length (e.g., Cox 1990, 1991, 1993; Shelton & Cox 1994; Slavin & Cox 1993). The bottom line is that with the porosity imperative gone, there is very little to suggest that hot gas might be common in the ISM. The remaining evidence involves only O VI and other high stage ions, the soft x-ray background, and the assumption of interphase thermal pressure balance. A reanalysis of the Copernicus O VI data (Shelton & Cox 1994) has shown that the observed ions are probably located within discrete disturbances (SNRs and superbubbles) and should not be attributed to "interfaces" of clouds immersed in a pervasive hot interstellar component. Thus, the details of the existing O VI data speak against the picture they have long been supposed to support. The jury is still out on the soft x-ray background, but much of it arises locally; that which does not is patchy, probably more consistent with an origin in discrete disturbances than in a pervasive phase. In addition, along some very low density sightlines, there is no appreciable x-ray excess as might be expected from a pervasive hot phase. And finally, we come to the evidence from interphase pressure balance—what confines the high latitude clouds? The answer is unclear, but from my earlier remarks on this general topic, it is clearly not appropriate to assume that it has to be a comparable thermal pressure from hot gas.

Diffuse Ionized Gas: Miller & Cox (1993) showed that the high latitude ionized gas studied by Ron Reynolds could be due to O star radiation, but that one would then expect

H alpha to be brighter above regions with concentrations of O stars. (This appears to be true in Perseus.) Another feature of this picture is that much of the apparently diffuse H alpha should arise in cloud boundaries illuminated by the ionizing radiation. The correlation between H alpha and 21 cm has been explored for one field (Reynolds, Tufte, Heiles, Kung, & McCullough 1995), with curious results. It will be explored much more generally when results are in from Reynolds's WHAM (Wisconsin H-Alpha Mapper) telescope.

Meanwhile there is a fly in this ointment also. Helium appears to be significantly less ionized in the diffuse ISM than hydrogen is (Reynolds & Tufte 1995; Heiles et al., in preparation). Dennis Sciama is probably quite happy about this (e.g., Sciama 1994), but the rest of us are wondering whether radiative transfer of diffuse radiation off cloud boundaries or some other effect could be the culprit. Perhaps the overluminosity of ionizing radiation from some B stars, as found with *EUVE* (Cassinelli et al. 1995) will turn out to alter the expected ratio of ionized helium to hydrogen sufficiently and save the day.

Warm Intercloud Gas in the ISM: Following the demise of the porosity imperative and the clarification of the O VI evidence, my personal view was that the warm intercloud component would soon return to fashion. (If Slavin's SNR bubbles are eventually observed, fashion will be much too weak a word.) But I am presently uneasy because there are GHRS spectra that appear to show that there are very long lines of sight with virtually nothing filling the space along them (e.g., Spitzer & Fitzpatrick 1993). I am uncertain whether a quasi-homogeneous warm intercloud medium could have been seen, and whether velocity crowding could have created apparent clouds where there are none. But I am steeling myself for the possibility that much of space is actually very close to empty.

Empty Spaces: In 1986, Priscilla Frisch asked me why I didn't consider the possibility that much of interstellar space could be effectively empty. At the time, I couldn't conceive of it, but I've been trying.

In a model of the z-dependent porosity due to SNRs and superbubbles, Ferrière (1995) found a very high porosity well off the plane of the galaxy, due almost entirely to defunct and dying superbubbles. They take a long time to dissipate. It is quite possible that their interiors could have cooled to essentially negligible thermal pressure well before the bubbles disappear. In such a situation, the bubble walls would be seen as ensembles of high latitude clouds, while the cavity could be a transient emptiness.

If flux ropes turn out to be a major feature of the interstellar mass and field configuration, then individual filaments of material could have appreciable cohesion, the space between them could perhaps be largely empty.

One might suppose that if near emptiness were common, it would soon become very hot, there are after all supernovae still, and even cosmic ray heating will be important at sufficiently low density. McKee & Ostriker used thermal evaporation of clouds to stabilize their model against thermal runaway, radiative cooling being less important at higher temperatures and lower density. But at sufficiently low density, things change. If there is too little material to thermalize a supernova ejecta's kinetic energy, a remnant will not "heat"; the ejecta will sweep through the emptiness until it finds matter to splat against. If the void is sufficiently large, the mass density within it remains negligible, the shock into the surrounding medium is immediately radiative and soon unobservable (S.J. Arthur 1995, private communication). Do you recall that the Crab Nebula appears to have hit only nothingness so far? Was that nothingness of the star's own making or was it a characteristic of the ambient medium?

Thermal Conduction and Thermal Evaporation: Thermal conduction is commonly neglected in hot gas studies, but it probably rarely should be (Slavin & Cox 1992). It can be suppressed by a tangled magnetic field, but it is often such a powerful transport phenomenon that a considerable amount of suppression would be required to curtail its tendency to flatten temperature profiles in hot gas (Tao 1995), and to prevent excavation of ridiculously low density cavities such as one finds, for example, in the Sedov solution. In situations in which the electron and ion temperatures are not equilibrated, one should even not ignore the effects of ion conduction (Cui & Cox 1992). Our group is presently constructing a model of the SNR W44 from which it clear that the centrally brightened thermal x-ray emission has just the characteristics expected of a remnant with thermal conduction included (Shelton, Smith, & Cox 1995). It would probably be instructive to consult students of the solar wind to learn what is known about the effective radial thermal conductivity in that context, across the spiraling magnetic field.

But saying that thermal conduction is active in regions of hot gas is not an invitation to suppose its effects are never suppressed. The structure of the strong gradient boundary between hot and cold gas is certainly altered from the field free case, and can have an enormous impact on one's conclusions regarding thermal evaporation of clouds (e.g., Slavin 1989; Borkowski, Balbus, & Fristrom 1990). One hopes that in time, observations of the ionic and kinetic structure in the boundary between the Local Cloud and the surrounding hot gas will clarify matters somewhat. At present, it is fairly safe to say that thermal evaporation of clouds is a theoretical possibility which has never found confirmation in the ISM.

Galactic Fountains: This is a thoroughly intriguing concept which has seen a fair amount of redefinition over the years. It was conceived in the days when hot gas was widely believed to pervade the galactic disk and burble up out of it into a fountain. Later it was the returning chimney effluent. Next it will probably be redefined to be the cooling hot gas in the high latitude extensions of superbubbles. It's chief purpose has been to explain the existence of high stage ions well off the plane of the Galaxy. There could well be no identifiable galactic fountain, but calculations of one's properties are useful in setting limits on the rate at which supernovae generate hot gas, and on the conditions in which that gas cools and recombines.

Galactic Wind: Cosmic rays leave the Galaxy; does anything else? One is sometimes left with the impression from studies of hot gas in clusters that as much mass leaves a galaxy in a wind as is condensed into stars. But this seems to involve mainly elliptical galaxies. Spirals with starbursts might also have appreciable winds, as might regions around some galactic nuclei, but when it comes to the Solar Neighborhood of the Milky Way, there is no evidence I know of to support the idea that there is a wind, other than that of the cosmic rays. But I'm not sure that the door is fully closed on interesting possibilities. Radiation pressure ejection of dust grains could change our sense of chemical evolution; Lyman alpha pressure on neutral hydrogen might be exciting. It could be important to know whether cosmic rays diffuse and escape the Galaxy individually, or leave more collectively when their local pressure overwhelms magnetic tension and they flare out of the Galaxy. (The later provides a natural way to understand the magnitude of the trapped cosmic ray pressure.)

Galactic Flares and Microflares: If there are galactic flares, do they suddenly hoist great quantities of material to high z, after which it rains back into the disk? Is such material heated to the point that it contains high stage ions? Do microflares (Raymond 1992) occur in the galactic halo, and if so, what are their characteristics? Are they significant actors or merely a source of noise in our observables, the lithium like ions of carbon, nitrogen, and oxygen?

REFERENCES

BREGMAN, J. N. & ASHE, G. A. 1991, in The Interstellar Disk-Halo Connection in Galaxies, ed. H. Bloemen, 387. Dordrecht: Kluwer

BORKOWSKI, K. J., BALBUS, S. A., & FRISTROM, C. C. 1990, ApJ, 355, 501

BOULARES, A. & COX, D. P. 1988, ApJ, 365, 544

BOWYER, S,, LIEU, R., SIDHER, S. D., LAMPTON, M., & KNUDE, J. 1995, Nature, 375, 212

COX, D. P. 1995, Nature, 375, 185

CASSINELLI, J. P. ET AL. 1995, ApJ, 438, 932; and Cassinelli these proceedings

COX, D. P., 1988, in Supernova Remnants and the Interstellar Medium, ed. R. S. Roger & T. L. Landecker, Cambridge Univ. Press, 73

COX, D. P. 1989, in Structure and Dynamics of the Interstellar Medium, ed. Tenorio-Tagle et al., Springer-Verlag, 500

COX, D. P. 1990, in The ISM in External Galaxies, ed. Thronson & Shull, Dordrecht: Kluwer, 181

COX, D. P. 1991, in The Interstellar Disk-Halo Connection in Galaxies, ed. H. Bloemen, Dordrecht: Kluwer, 143

COX, D. P. 1993, in Massive Stars: Their Lives In The Interstellar Medium, 1993, ed. J. P. Cassinelli & E. B. Churchwell, ASP Conf. Series, 35, 402

COX, D. P. & REYNOLDS, R. J. 1987, ARA&AA, 25, 303

CUI, W. & COX, D. P. 1992, ApJ, 401, 206

ELLISON, D. C., REYNOLDS, S. P., ET AL. 1994, PASP, 106, 780

FERRARA, A. 1993, ApJ, 407, 157

FERRIÈRE, K. M. 1995, ApJ, 441, 281

FRANCO, J. FERRINI, F., & FERRARA, A., & BARSELLA, B. 1991, ApJ, 366, 443

FIELD, G. B., GOLDSMITH, D. W., & HABING, H. J. 1969, ApJ, 155, L149 (FGH)

FRAIL, D. A. WEISBERG, J. M. CORDES, J. M., & MATHERS, C. 1994, ApJ, 436, 144

MACIEJEWSKI, W., MURPHY, E., LOCKMAN, F. J., & SAVAGE, B. D., 1995, ApJ, in preparation

MARTOS, M. 1993, Ph.D. thesis, UW-Madison

MCKEE, C. F. & OSTRIKER, J. P. 1977, ApJ, 218, 148 MO

MILLER, W. W. III, & COX, D. P. 1993, ApJ, 417, 579

RAYMOND, J. R. 1992, 384, 502

REYNOLDS, R. J., TUFTE, S., HEILES, C., KUNG, D., & MCCULLOUGH, P. 1995, ApJ, in press

REYNOLDS, R. J. & TUFTE, S. 1995, ApJ, 439, L17

SCIAMA, D. 1994, ApJ, 426, 65

SHELTON, R. L. & COX, D. P. 1994, ApJ, 434, 599

SHELTON, R. L., SMITH, R. K., &, COX, D. P. 1995, BAAS, 186th AAS, late abstracts

SLAVIN, J. D. 1989, ApJ, 346, 718

SLAVIN, J. D. & COX, D. P. 1992, ApJ, 392, 131

SLAVIN, J. D. & COX, D. P. 1993, ApJ, 417, 187

SPITZER, L. & FITZPATRICK, E. L. 1993, ApJ, 409, 299

TAO, L. 1995, MNRAS, in press

WOLFIRE, M. G., HOLLENBACH, D., MCKEE, C. F., TIELENS, A. G. G. M., & BAKES, E. L. O. 1995, ApJ, 443, 152