THE YIN AND YANG OF X-RAY/RADIO DIAGNOSTICS OF COLLIDING FLOWS

K. G. Gayley
University of Iowa
203 Van Allen Hall, Iowa City, IA, 52242
KENNETH-GAYLEY@UIOWA.EDU

Abstract

This conference juxtaposes observations from nearly opposite ends of the electromagnetic spectrum, so it is especially appropriate to consider the conceptual value of analyzing physical phenomena in relief against opposite extremes of limiting assumptions. Colliding stellar winds and supernovae that blow large bubbles in rich star-forming regions provide ample opportunity for this approach, and this review considers the contrasting roles of thermal versus non-thermal emission, adiabatic versus radiative cooling, homogeneous versus clumpy structure, and ram pressure versus magnetic flow confinement, in this general context. An irony of such a yin/yang approach is that it too has contrasting advantages and disadvantages, since juxtaposing opposites on the one hand helps us see in high-definition contrast, but on the other hand is essentially an effort to understand an elephant from just its signature trunk and tail without the many significant details in between. Effective use of this approach must keep in mind both the advantages and limitations of thinking in simplified extremes.

1 Introduction

The key questions that arise when attempting to extract diagnostic information about wind collisions and wind-blown bubbles include the following. What can we learn about stellar winds by watching them ram into things? What do radio and X-ray observations tell us about these collisions? And, which diagnostics are most sensitive to which physical processes? As we address these questions, we hope to learn about the properties of the colliding flows, including their mass, momentum, and energy fluxes, their entrained magnetic fields, and the properties of the ambient material the flows encounter. A central motivation for this conference is the valuable and complementary nature of radio and X-ray diagnostics for accomplishing this goal.

The good news is that the long radio wavelengths, due to diffraction, experience ultra-low attenuation in transit, and using interferometry they provide excellent spatial resolution for studying the morphology of the structures that result from wind-blown bubbles. This regime also allows clear signatures of both thermal free-free emission and non-thermal electron acceleration, allowing us to apply the accompanying diagnostics with greatly reduced ambiguity. X-ray observations, on the other hand, also suffer fairly low attenuation at the higher energies capable of punching through intervening matter, and they are an important cooling channel for the high-temperature gas resulting from high-speed flow collisions, so they give direct information about the energy budget in this gas. They also contain temperature-sensitive spectral lines that provide additional information about energy thermalization.

However, with this good news also appears some bad news, which must be carefully considered before over-interpreting the results. For the radio regime, non-thermal emissions are sensitive to poorly constrained aspects of the particle acceleration process and magnetic field geometry, while thermal emissions are generally an insignificant component of the total energy budget. Also, the collisional nature of free-free emissions make them overly sensitive to high-density regions and the unknown degree of clumping. Meanwhile, the X-ray regime may experience enough extinction to obscure important sources and interfere with spatial correlations with radio data, especially when the sources are wind/wind collisions in close binaries. And even X-rays will not reveal much of the energy thermalized in low-density gas that cools adiabatically, since much of the energy will be shunted downstream in the form of bulk flows that may be difficult to resolve or constrain. Finally, the collisional nature of X-ray emission processes mirror the radio over-sensitivity to clumpy material, introducing ambiguity in the inferred volume-averaged fluid properties. Notwithstanding these limitations, a combination of radio and X-ray observations offers considerable promise for understanding the nature of wind/wind collisions and wind-blown bubbles at many spatial scales.

2 General diagnostics in the radio and X-ray regimes

As this conference brings together practitioners at both ends of the electromagnetic spectrum, it should perhaps not be assumed that each is familiar with the basic types of diagnostics applied by the other. However, a common issue for both radio and X-ray emission is whether the emitting electron population is thermally distributed or accelerated into more gradually falling power-law-type distributions. Typically this is tantamount to asking whether the emission comes from the dominant population or a trace but energetically significant tail. The answer is usually inferred from the shape of the emergent continuum spectrum.

For the radio regime, the period of the waves is nonresonant with the much longer thermal electron interaction timescales, and so each frequency is more or less alike in the emission process. Thus an optically thin thermal radio spectrum is typically rather flat. However, self-absorption in optically thick plasma drives the spectrum toward the Planck function, which scales roughly as frequency squared in the radio. Thus in all, a spectrum that rises with frequency until it reaches an optically thin plateau would be characteristically thermal. This is in stark contrast to non-thermal synchrotron emission in the presence of particle acceleration and magnetization, which is resonant with the electron gyro frequency and so closely mimics the accelerated particle distribution function, and is therefore expected to be steeply falling with frequency. When observing in a given radio band, this implies that a flat or rising spectrum is indicative of thermal emission, and a falling spectrum is likely to be non-thermal. When observing over a much broader frequency domain, the lower frequency end is more likely to be dominated by non-thermal emission, and the higher by thermal, although in extreme environments of particle acceleration the resonant character of the non-thermal component may allow it to completely swamp the thermal.

The X-ray continuum may also exhibit either thermal or non-thermal components, and there is the additional possibility of echoing the radio spectrum via inverse Compton scattering from an accelerated population. Detection of non-thermal synchrotron emission yields constraints on the magnetic fields, while inverse Compton emission depends on the illuminating continuum, and of course both processes depend on the distribution of accelerated electrons, and must be differentiated from any thermal continuum present. Extracting this much information from a single spectrum is exceedingly difficult, so it is important to narrow down the possibilities. One way to ascertain the relative contribution to the X-ray continuum from thermal sources in hot highly ionized gas is to look for the prominent Fe XXV Kα line complex near 6.7 keV. If this line is comparatively weak relative to the continuum, it suggests that the continuum is diluted with a corresponding amount of non-thermal emission. However, care must be paid not to confuse the highly excited Fe XXV lines with the X-ray fluorescent low-ionization Fe line at 6.4 keV, which instead gives information on the presence of nearby molecular clouds (Sunyaev, Markevitch & Pavlinsky 1993).

3 Superbubble models

Armed with these powerful diagnostics, confrontation with the predictions of specific models becomes appropriate. One area of recent theoretical advance is the modeling of the “superbubbles” blown by a collection of many hot-star winds in young clusters. Chevalier & Clegg (1985) and Canto, Raga & Rodriguez (2000) advanced a self-similar flow model in which many stellar winds are shocked and thermalized into a single giant pressure-driven superwind, and Mac Low et al. (1998) postulated such systems could be detectable X-ray sources. In this model, the wind energy fluxes serve to pressurize the superbubble, which drives an energy-conserving shell of swept-up ambient gas. Most of the mass and energy in the system resides in this shell, which enables efficient energy conversion if it completely surrounds the hot shocked gas. In the comparison between whether it is the wind energy input or its momentum input that is more relevant to the driving of the interstellar material, it bears noting that significant holes and breakouts of the interior hot gas will limit the confinement efficiency and tend toward flows that merely convert the wind *momenta* into that of the swept up material, akin to linearly directed snowplows, whereas for an isotropically expanding dense shell it is the efficient conversion of wind *energy* that is relevant.

If the flow is assumed to be fully confined and self-similar, the predicted thermal X-rays were shown by Canto, Raga & Rodriguez (2000) to yield both a diffuse signature of the hot confined gas as well as discrete sources from the reverse shocks that the many stellar winds initially confront, and these predictions have invigorated the observational study of superbubbles. The young Arches cluster has been used as a proving ground for testing this general model, and the model of Raga et al. (2001) predicted a detectable level of diffuse X-rays which were then seen by Yusef-Zadeh et al. (2002). This success opens a new window onto these processes, although one possible problem is that the observed fluxes are actually much higher than quoted in the theory paper, suggesting a possible embarrassment of riches for observational detectability, but at the meeting the point was made that this may be traced to a typographical error in the Raga et al. paper (Silich 2004, private communication). It is thus somewhat unclear if the models and observations are currently in agreement or if additional modifications are needed, but no doubt this matter will be resolved shortly by the growing synergy between observation and theory in this field.

If the observed X-ray fluxes are indeed high, one possible explanation relates to the point made above that thermal X-ray emissivities per volume have a density-squared sensitivity to clumping. However, cluster outflows would be expected to have densities of order $n_e \sim 10^{-2}$ cm^{-3}, which would be expected to fall in the adiabatic cooling regime over flow timescales. The advantages of this adiabatic limit include the fact that the energy bookkeeping is easier when losses are negligible, the high temperatures allow X-rays to be produced, and the high pressures resist clumping and simplify the diagnostic interpretation. However, as always there is another side to the coin, and the disadvantages include the fact that most of the energy is not being directly observed when the cooling is adiabatic, and so the radiative efficiency becomes a key parameter for determining the connection between observed brightnesses and the physical conditions that generate them. Thus although adiabatic environments tend to suppress clumping, any clumping that does appear has a more significant impact on radiative efficiency and observed fluxes. Thus it is important to consider the processes that could yield over-densities, and their potential impact on diagnostic inferences.

4 Possible importance of clumping

When flows collide, it is natural to expect density compressions, but whether or not these are limited by the factor-4 adiabatic shock ratio or are enhanced further by radiative cooling or other instabilities is a complex matter for detailed hydrodynamic simulations. For example, Stevens, Blondin & Pollock (1992) demonstrate the thin-shell instability in the strongly cooled dense colliding winds from close binaries. This instability wraps up a complex sheet of high density compressed material that would efficiently convert flow kinetic energy into radiation and dramatically enhance thermal fluxes. The impact on particle acceleration and non-thermal emission is a particularly difficult problem. On the other hand, in lower density wind collisions they find that adiabatic instabilities are far less dramatic, although the Kelvin-Helmholtz shear instability may still give rise to density contrasts that are significant. Thus in general the low-density high-temperature environment of the colliding winds in a superbubble would tend to favor incompressible turbulent modes rather than compressive instabilities, and yet the sensitivity of the observed radio and X-ray thermal emission to the actual density distribution creates a need for a better understanding of compressive and turbulent processes on these scales.

5 Contrasting clumping models

The field of compressible turbulence is in its infancy, and most clumping models to date are necessarily rudimentary. At first glance the simplest approach to clumping would be to assume that the gas is compressed into equal-density blobs surrounded by essentially empty vacuum, which allows the clumping of a given amount of mass to be characterized by a single parameter, the volume "filling factor" f. However, it will be argued here that this seemingly innocuous approach makes assumptions that may be neither warranted nor necessary, even in the context of a simple one-parameter family of mass-conserving density distributions. Specifically, if one assumes that the volume V is distributed over density ρ according to a given $dV/d\rho$ and considers density moments of the form

$$< \rho^n > V \; = \; \int d\rho \, \frac{dV}{d\rho} \rho^n, \tag{1}$$

then it is clear that the filling-factor approach implies that all moments receive contribution from the same characteristic density. To see the more general case, let us define for each moment $< \rho^n > V$ its its own characteristic density ρ_n, such that half of the contribution to that moment comes from densities above ρ_n:

$$\int_0^{\rho_n} d\rho \, \frac{dV}{d\rho} \rho^n \; = \; \frac{1}{2} < \rho^n > V. \tag{2}$$

In the filling-factor description of $dV/d\rho$, all ρ_n are the same, but this is not a general requirement of one-parameter fits to the density distribution. Since all such distributions are in a sense equally simple, is it physically appropriate to attach this additional constraint?

Note for clarity that the $n = 0$ moment is the volume V, the $n = 1$ moment is the mass M, and the $n = 2$ moment is the emission measure EM. Thus in the filling-factor picture, we have

$$EM \; = \; \frac{M^2}{fV} \tag{3}$$

which may be viewed as a way to characterize the fit parameter f. But this approach somewhat insidiously requires that the same characteristic clump density, $< \rho > /f$, is responsible for both the bulk of the mass and the bulk of the thermal emission, i.e., the same physical clumps comprise the dominant contribution to both. This allows a more direct connection between mass and emissivity than may be physically appropriate, since it is entirely possible that *different* particles are actually the dominant contributors to different moments. Thus numerous but lower density clumps might account for the mass content while rarer but higher density regions account for the density-squared type emission, and compressible influences on these two populations might have different impact on density-type diagnostics versus density-squared type.

This complexity cannot be addressed in the filling-factor approach, and so as an alternative, of particular interest is a log-normal $dV/d\rho$ distribution. Such a distribution may be obtained by any process that shuffles the densities of the clumps in a scale-invariant way, i.e., yields a random walk of fixed step size in log ρ space. The random walk will yield a Gaussian in this space, i.e., a log-normal distribution. The peak of the distribution always shifts to lower density, and the magnitude of this shift, $\Delta \ln(\rho)$, is the only free parameter in a mass-conserving distribution, since this shift also equals the width of the Gaussian. Therefore we also have a one-parameter family of fit functions. As for the filling-factor approach, most of the volume is occupied by low-density gas, but now each density moment $< \rho^n >$ is associated with a different characteristic density ρ_n. Indeed, it is straightforward to show that

$$\ln(\rho_n) \; = \; (2n - 1)|\Delta \ln(\rho)|, \tag{4}$$

implying that different densities and so different clumps are predominantly responsible for the mass and the emission measure, for example. This ability for different clump densities to dominate the different density moments seems a more general way to treat the effects of clumping when using a simple one-parameter distribution.

Another important difference between the filling-factor and log-normal approaches is the way in which the fluid quantities of interest scale with the degree of clumping. In a one-parameter clump model, one way to measure the degree of clumping is to use the volume filling factor f_1 that is relevant for the total mass, i.e., $f_1 V \; = \; M/\rho_1$. Or if one considers the volume filling factor f_2 that is relevant for the emission measure, then $f_2 V \; = \; EM/\rho_2^2$. In the standard filling-factor picture, $f_2 \; = \; f_1 \; = \; f$, but for the log-normal distribution, it is easy to show that $f_2 \; = \; f_1^4$! This implies that if the mass comes from a small fraction f_1 of the total volume, then the emission will derive from a much smaller fraction f_1^4, as a result of the implied density hierarchy. Also, if EM and V are known from observations, then the inferred M will scale like $\sqrt{f_1}$ in the filling-factor picture, but like f_1 in the log-normal approach, so the latter shows a rather more sensitive dependence of the inferred mass on the amount of compression. Thus it appears that even the simplest one-parameter clumping models may yield qualitatively different behavior, and one again wonders if these simplified concepts of clumping allow us to see in high-definition contrast against the homogeneous case, or if we are missing a complex elephant by focusing only on its trunk or its tail.

6 Blowouts, chimneys, and stalled superbubbles

Returning to the issue of superbubbles and how efficiently they can be driven by stellar winds into the ambient medium, as issue that appears is whether it is the stellar wind momentum or energy fluxes that are most relevant. Note that this is a question of efficiency, since complete energy conversion from the winds to the ambient gas is the maximum efficiency, whereas simple momentum flux conversion is highly inefficient at blowing large bubbles. The issue is also related to whether the flow within the bubble is subsonic (as derives from energy conversion) or supersonic (as derives from mere momentum conversion), because a subsonic flow exerts forces primarily via gas pressure and does work by exerting this momentum flux continuously, effectively reusing the momentum over and over, whereas supersonic flows can only exert their momentum flux once. For this reason, the volume in a superbubble which is dominated by the supersonic winds is generally quite small relative to the volume filled with shocked high-pressure subsonic gas. However, one process that limits the bubble-driving efficiency of this hot gas is holes or openings in the bubble boundary, since then supersonic flows will blast through, returning the energy to bulk flow motion and once again limiting the driving efficiency to the momentum-flux limit. In effect, the bubble is "popped," and bubbles with shredded exteriors (due to under-dense channels in the ISM or violent supernovae) will not be driven to the same large size as bubbles that retain the integrity of their confining boundaries.

Observationally, this possibility gives rise to breakouts (Magnier et al. 1996) and chimneys (Terebey et al. 2003) that are observed as jet-like flows emanating from superbubble regions on molecular-cloud or even galactic scales. It is typical for bubbles and superbubbles to be much smaller than would be predicted by simple energy-conserving arguments, and this is one possible explanation.

Another interesting possibility that receives observational support from improved spatial resolution is that the bubble interior may be polluted by evaporation from embedded clumps. Adding low-energy gas to the high pressure interior will drop the temperature accordingly (Silich et al. 1996), and may drive the interior flows toward an inefficient supersonic domain (Pittard, Dyson & Hartquist 2001). Radiative losses will be enhanced by the elevated densities of evaporating gas, and so it is also possible to reduce the pressure driving the bubble via energy loss channels.

Evaporating clumps within the supersonic wind regions, on the other hand, will further reduce the volume occupied by winds, because a supersonic wind passing an evaporating clump will conserve momentum flux and this will thermalize some of its bulk kinetic energy as mass is added. The reduced momentum flux lowers the wind ram pressure and weakens the shocks, as some of the necessary conversion of bulk momentum flux into pressure has already been achieved by the mass loading process. The pressure-dominated region of the bubble is therefore enhanced at the expense of the small wind-dominated regions, although the global bubble pressure depends on the energy content so should be minimally affected unless radiative cooling is enhanced by the mass loading.

7 Potential role of magnetic fields

In the magneto-hydrodynamical (MHD) limit, magnetic fields are frozen into the plasma on astrophysical scales. Thus either the plasma carries the B fields along, or else it moves like beads along externally fixed wires, depending on whether the plasma or magnetic energy densities are higher. The latter case may yield significantly filamentary structures, and indeed Yusef-Zadeh (2003) has proposed that the radio filaments seen near the Galactic center (Yusef-Zadeh, Morris & Chance 1984) may be magnetic field lines that connect to distant molecular clouds, where wind collisions create an accelerated plasma component that streams along the field lines.

Magnetic fields may also affect the outflow dynamics of the bulk of the thermal plasma whenever the Alfven speed is dynamically important, which for wind speeds of order 1500 km s^{-1} requires $B > 6\times10^{-4}\sqrt{n}$. This occurs either far from the stars where the plasma density is low (e. g., Ferriere, Mac Low & Zweibel 1991) or close to the stars where the B field is strong (e.g., ud-Doula & Owocki 2002). Observations of Zeeman splitting in molecular clouds indicates that the characteristic $B \sim 10^{-3}$ G, which is sufficient to explain synchrotron emission when an accelerated population is present, and this implies that the Alfven speed may be dynamically important whenever the density falls below roughly several particles per cc. Closer to stars, where local dipole-type enhancements to the B field may appear due to fossil fields or stellar dynamos, the impact on stellar winds may be quite dramatic, as closed-field topologies can induce wind/wind collisions like two freight trains on the same track. This has been suggested as a means of producing hot plasma concentrations at the magnetic equator of chemically peculiar hot stars (Shore & Brown 1990) as well as point-like X-ray sources in regions where young stars are present (Babel & Montmerle 1997).

Another way that magnetic fields are relevant is in allowing cyclotronic particle motions to transport negative or positive momentum across a velocity difference, which corresponds respectively to energy thermalization or particle acceleration. Thus magnetic fields create a type of viscous drag that can thermalize shear motions, as well as a compressive viscosity that can extract thermal energy and produce a non-thermal tail population. Hence they may play a role in both thermal and non-thermal emissivities, and they certainly are central to synchrotron emission. Unfortunately, their vector nature introduces substantial line-of-sight ambiguity, and may cause turbulent components to spatially average to zero on resolvable scales, so that accurate description of large-scale fields is difficult and detection of subscale fields is a challenge. To make progress it is typical to assume that large-scale fields are constant or bipolar while small-scale fields are in equipartition with the gas pressure, but of course in future it will be necessary to introduce more and more precise descriptions of the fields as better observations become available.

8 Conclusions

Supersonic flow collisions generate hot gas and accelerated particles that emit thermally and non-thermally in both the radio and the X-ray regimes. The many powerful diagnostics offered by these regimes in this context come with important advantages, but it is also important to recognize their disadvantages when making observational interpretations. In the radio, the resonant character of non-thermal synchrotron emissions allow it to trace the accelerated electron distribution, but this only represents the tail of the full distribution, and is sensitive to both the energization process and the geometry and strength of the B field. Thermal radio emissions are important in high-density regions and do sample the dominant mass component, but represent a trace energy loss channel and are oversensitive to density fluctuations. Thermal X-rays, on the other hand, are a good diagnostic of density and are also temperature sensitive, but only for the hot gas, and the problem of possible clumping dependence again appears. The X-ray lines, particularly around 6.7 keV, are also good diagnostics of thermal plasma and can be compared to the continuum to constrain the non-thermal emission, but care must be taken to separate them from $\sim$ 6.4 keV fluorescent emissions from low-ionization stages of Fe in nearby molecular clouds.

Low-density environments support adiabatic analysis, which has the advantage of simplifying the energy budget, but the main energy channels will not be observed directly and the radiative efficiency and clumping effects become important to constrain. In this regard, the standard filling-factor approach may be too naive to incorporate all of the conceptually important effects. Mass loading may serve to limit the adiabaticity by introducing additional radiative cooling, and the resulting momentum sharing provides a natural mechanism for flow thermalization prior to encountering large-scale shocks, whereas blowouts and chimneys may limit the degree of energy thermalization that ultimately occurs. And finally, the presence of ordered magnetic fields may channel flows close to stars where they are strong or far from stars where the density is low, and their unique geometries may contribute to unusual features like the radio filaments that crisscross the galactic center region. Even disordered fields play a role as a pressure term in the bulk plasma, as accelerators in the tail components, and as an influence on the nature of synchrotron emission. Disentangling all the strengths and weaknesses of these various conceptual tools will require a vigorous effort by the community, but good progress in this direction is clearly already being made, as evidenced by the many other contributions to this proceedings.

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