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# 3-D explosions: a meditation on rotation (and magnetic fields)

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## 1.1 Introduction: a brief time for history

There has been a great deal of progress in the thirty-five years or so that I have been working on supernovae and related topics. Two of the classical problems have been with us the whole time: what makes core collapse explode, and what are the progenitors of Type Ia supernovae? This workshop, indeed, the perspectives of three-dimensional astrophysics applied to these problems, gave encouraging evidence that breakthroughs may be made in both of these venerable areas.

On the other hand, what a marvelous array of progress has rolled forth with ever increasing speed. We have an expanded botany of supernovae classification: Type Ia, Ib, Ic, Type IIP, IIL IIb, IIn; but, of course, more than mere classification, a growing understanding of the physical implications of these categories. Neutron stars were discovered as rotating, magnetized pulsars when I was a graduate student, and the extreme form, magnetars, has now been revealed (Duncan & Thompson 1992). The evidence that we are seeing black holes in binary systems and the centers of galaxies has grown from suspicion to virtual certainty, awaiting only the final nail of detecting the black spot in a swirl of high-gravity effects. Supernova 1987A erupted upon us over 16 years ago and is still teaching us important lessons as it reveals its distorted ejecta and converts to a young supernova remnant before our eyes.

There have also been immense theoretical developments. Focus on core collapse has stimulated so much great work on neutrino transport: the invocation of weak neutral currents and neutrino-nucleon scattering; the understanding that neutrinos can and will become degenerate at the highest densities and the concomitant implications for the dynamics and the formation of the homologous core. More recently we have come to general understanding that a prompt shock is unlikely to make an explosion, but that significant layers of the proto-neutron star will be convective with important implications for the neutrino transport. Techniques of neutrino transport have evolved from simple diffusion to full Boltzmann transport. SN 1987A showed dramatically that we are on the right track, even if the details, even important physics, may be missing: core collapse with the predicted production of neutrinos does occur! In terms of the "other mechanism," our understanding has evolved from detonations to deflagrations, to the current paradigm of delayed detonation models. The recent understanding of the associated combustion physics has blossomed with the computational ability to do the required three-dimensional modeling.

Finally, the last few years have seen the birth and maturation of a field that was hinted at long ago, but came to fruition only recently, the systematic study of the polarization of supernovae. This technique has substantially altered our view of core collapse. It was only a few years ago that polarization was still regarded as an oddity, perhaps limited to a few peculiar events. In the last year, the idea that core collapse is asymmetric has become sufficiently accepted that papers are now written saying "as is well known, core collapse is asymmetric" without providing any reference to the hard labor required to establish that! Overnight, it seems, the wonders of the three-dimensional world have become revealed wisdom. The revelations of polarized core collapse have been the most distinct so far, but their implications are far from understood. The application of polarization to Type Ia supernovae had lagged somewhat in drama because the polarization is generally smaller, but this workshop served to provide evidence that important three-dimensional distortions are ubiquitous, and important, in Type Ia as well.

Besides all these developments that have been so central to the development of supernova science, the last few years have seen two outstanding developments that have cast supernovae research, already one of the most central and important in astrophysics, onto broader stages. What a time was 1997/1998! Careful studies of Type Ia supernovae revealed the acceleration of the Universe with the implication of the pervading dark energy. In virtually the same time frame, the discovery of optical transients associated with gamma-ray bursts and then SN 1998bw led to the connection of gamma-ray bursts with supernovae, probably some variety of Type Ic. For a mature field, the study of supernovae had a great deal of life left! Since Type Ia and Type Ic have been especially near and dear to me, this was about more excitement than my mature heart could stand.

I cannot do justice to all the great work on supernovae that has been done over my career, but I would like to touch on one other bit of history, a development that was critical for so much else that followed. I distinctly recall that when I was in graduate school there was a raging debate concerning the nature of the spectra of Type Ia, then called just Type I, supernovae. Some people argued that the spectrum near maximum consisted only of absorption lines and provided the interpretation of the absorption minima in terms of atomic features. Others insisted that the spectrum consisted purely of emission lines and provided an interpretation of the flux peaks, totally incongruent with the first interpretation, of course. David Branch provided the insight that we were looking at P-Cygni lines, hence a blended mix of emission and blue-shifted absorption. That was the insight needed to convince the world that the key feature in the spectrum of a Type Ia was Si II. From that it followed that the presence of silicon and other intermediate mass elements ruled out pure detonation models. This was the base on which so much subsequent analysis of supernovae of all types was built. More work, especially from Bob Kirshner and colleagues revealed that, with patience, the spectrum does evolve to be dominated by emission lines. Type Ia, like all supernovae, eventually evolve to a "supernebular" phase.

## 1.2 Type Ia

The combination of ever more thorough searches both by people at the eyepiece and by computer-driven telescopes, subsequent multi-wavelength follow-up, and theoretical and computational study has brought the study of Type Ia supernova to an impressive level of maturity. After a spirited debate, the conclusion that Type Ia are not merely thermonuclear explosions in white dwarfs, but specifically explosions in carbon/oxygen white dwarfs of mass very nearly the Chandrasekhar mass is now essentially universally accepted (Höflich & Khokhlov 1996; Nugent *et al.* 1997; Lentz *et al.* 2001). Even more precisely, the paradigm of a slow initial subsonic deflagration phase followed by a rapid supersonic, shock-mediated detonation phase (Khokhlov 1991) has been richly successful in accounting for the observed properties of Type Ia (Höflich 1995). It accounts for the existence of iron-peak elements in the center of the explosion and layers of intermediate mass elements in the outer layers, essentially by design. It also gives a framework in which to understand the variety of light curve shapes with lower transition densities leading to less nickel, and dimmer, cooler, faster light curves (Höflich *et al.* 1996), and it has successfully made predictions about infrared spectra (Höflich *et al.* 2002) and polarization properties (Wang, Wheeler & Höflich 1997; Howell *et al.* 2001). *Delayed detonation works!*

This success has put focus on a wonderful physics problem, the deflagration to detonation transition, or DDT, that astrophysics shares with a host of terrestrial combustion issues. This is a hard problem on Earth or off! One of the most interesting developments in recent years has been the resonance of terrestrial and astrophysical combustion studies. There has been dramatic progress in understanding DDT in laboratory, shock-tube environments by means of sophisticated computational studies of shock-flame interactions (Khokhlov & Oran 1999) and DDT in enclosed environments where boundaries and reflected shocks play a key role (Khokhlov, Oran & Thomas 1999). Still, the astrophysical problem, one of unconfined DDT, remains elusive. This is a quintessential multi-dimensional problem, one for which several promising lines of attack are underway.

The wealth of knowledge of Type Ia revealed by optical studies is too large to summarize here, but it has been amplified and complemented in recent years by studies in the near infra-red. The NIR is an especially powerful spectral range to study because lines are less blended and the continuum is nearly transparent so one sees all the way through the ejecta with a single spectrum probing all the important layers simultaneously. This technique was pioneered for all supernovae by Peter Miekle and his collaborators and is rapidly coming to the fore as a major tool in the study of Type Ia. SN 1999by was a subluminous Type Ia that was, not incidentally, significantly polarized (Howell *et al.* 2001). Höflich *et al.* (2002) showed that a delayed detonation model selected to match the light curve provided a good agreement with the NIR spectra and revealed the products of explosive carbon burning in the outer layers and products of incomplete silicon burning in deeper layers. The results were inconsistent with pure deflagration models or merger models that leave substantial unburned matter on the outside. The data also seemed incompatible with the mixing of unburned elements into the center as predicted by pure deflagration 3-D models. Three-dimensional models in which the inner unburned matter undergoes a detonation, the current most realistic manifestation of the delayed detonation paradigm as presented here by Gamezo *et al.* alleviate that problem. Marion *et al.* (2003) have presented NIR spectra of "normal" Type Ia (see also Hamuy 2002) and shown that the outer layers of intermediate mass elements are not mixed, that very little unburned carbon remains in the outer layers, and perhaps revealed Mn, a sensitive probe of burning conditions.

Another important development concerns work on the quasi-static phase of carbon burning that follows carbon ignition and precedes dynamic runaway. This important "smoldering" phase had not been critically re-examined since the initial study of Arnett (1969). Höflich & Stein (2002) showed that the convective velocities in this phase can exceed the initial speeds of the subsequent deflagration front. This means that the "pre-processing" of the white dwarf by this smoldering phase and the resulting velocity field, rather than the pure Rayleigh-Taylor driven deflagration, will dominate the early propagation of the burning front. This is a crucial, multidimensional, insight that will foment much work in the near future to understand all the implications.

Finally, it is necessary to repeat that polarization studies have revealed that Type Ia are polarized and hence asymmetric (Wang, Wheeler & Höflich 1997). It may be that the subluminous variety are more highly polarized and perhaps more rapidlly rotating than the "normal" type (Howell *et al.* 2001). It may also be that, although the polarization is generally low, all Type Ia are polarized at an interesting level if appropriate, sufficiently accurate observations are made (Wang *et al.* 2003a). This has clear implications for the quest to answer the old problem of whether Type Ia arise in binary systems and, if so, as we all believe, what sort? The asymmetries might also be teaching us lessons yet ungleaned about the combustion process which is undoubtedly complex and three dimensional. The asymmetries must be understood in order to use Type Ia with great confidence as we move to the next phase of cosmological studies where exceptionally precise photometry and tight control of systematic effects will be necessary to probe the equation of state of the dark energy.

In any case, the lesson of recent history and of this workshop is that Type Ia supernovae are three dimensional!

## 1.3 Asymmetric core collapse

If anything, the polarization studies have had even more dramatic impact on core collapse supernovae. All core collapse supernovae adequately observed are found to be polarized and hence asymmetric in some way (Wang *et al*. 1996; Wang *et al.* 2001, 2002, 2003b; Leonard *et al.* 2000; Leonard & Filippenko 2001; Leonard *et al.* 2001, 2002). Many of these events are substantially bi-polar (Wang *et al.* 2001). The fact that the polarization is higher as one sees deeper in and is higher when the hydrogen envelope is less, strongly indicates that the very machine of the explosion deep in the stellar core is asymmetric and probably predominantly bi-polar. SN 1987A reveals similar evidence (Wang *et al.* 2002). Other famous "spherically symmetric" supernovae are those that gave rise to the Crab Nebula and to Cas A.

Complementary computational work has shown that jet-induced explosions can produce the qualitative asymmetries that are observed (Khokhlov *et al.* 1999, see also MacFadyen *et al.* 2001 Zhang, *et al.* 2003). Khokhlov & Höflich (2001) and Höflich, Khokhlov & Wang (2001) have shown that asymmetric nickel deposition by a jet-like flow can produce polarization by asymmetric heating and ionization even in an otherwise spherically-symmetric density distribution. This very plausibly accounts for the early low polarization in Type II supernovae that grows as the underlying asymmetry is revealed.

The large question remains as to what causes the jet-like flow. My bet is that this involves rotation and magnetic fields at the deepest level. Rotation alone can affect neutrino deposition, but the case can be made that rotation without magnetic fields is highly unlikely. Akiyama *et al.* (2003) have presented a proof of principle that the physics of the magneto-rotational instability (MRI: Balbus & Hawley 1991, 1998) is inevitable in the context of the differentially-rotating environment of protoneutron stars. The magnetic fields can in turn affect the neutrino transport. The ultimate problem of core collapse is intrinsically three-dimensional involving rotation, magnetic fields, and neutrino transport. We have known this all along (despite, not because of, cheap shots after core collapse talks in which some joker always asks "but what about rotation?" or "but what about magnetic fields?"), but the new polarization observations demand a new, integrated view. This makes a devilishly hard problem even harder. Progress will come by isolating and understanding pieces of the problem and eventually sticking them together.

## 1.4 The magneto-rotational instability and core collapse

The advantage of the MRI to generate magnetic field is that while it works on the rotation time scale of $\Omega^{-1}$ (as does field-line wrapping), the strength of the field grows exponentially. This means that from a plausible seed field of $10^{10}$ to $10^{12}$ G that might result from field compression during collapse, only $\sim$7–12 e-folds are necessary to grow to a field of $10^{15}$ G. That is only $(7\text{–}12)/2\pi \sim 1\text{–}2$ full rotations or $\sim$10–20 ms for expected initial rotation periods of order 10 ms. Furthermore, while the growth time may depend on the seed field, the final saturation field is independent of the seed field (unlike a linear wrapping model that ignores the complications of reconnection, see Wheeler *et al.* 2000, 2002, for examples and other references).

Core collapse will lead to strong differential rotation near the surface of the protoneutron star even for initial solid-body rotation of the iron core (Kotake, Yamada & Sato 2003; Ott *et al.* 2004). The criterion for instability to the MRI is a negative gradient in angular velocity, as opposed to a negative gradient in angular momentum for the Rayleigh dynamical instability. This condition is broadly satisfied at the surface of a newly formed neutron star during core collapse and so the growth of magnetic field by the action of the MRI is inevitable. More quantitatively, when the magnetic field is small and/or the wavelength is long ($\mathrm{kv_a} < \Omega$) the instability condition can be written (Balbus & Hawley 1991, 1998):

$$N^2 + \frac{\partial \Omega^2}{\partial \ln \mathrm{r}} < 0, \tag{1.1}$$

where N is the Brunt-Väisälä frequency. Convective stability will tend to stabilize the MRI, and convective instability to reinforce the MRI. The saturation field given by general considerations and simulations is approximately given by the condition: $\mathrm{v_a} \sim \lambda\Omega$ where $\lambda \lesssim \mathrm{r}$ or $\mathrm{B}^2 \sim 4\pi\rho \mathrm{r}^2\Omega^2$ where $\mathrm{v_a}$ is the Alfvén velocity.

These physical properties were illustrated in the calculations of Akiyama *et al.* (2003) who used a spherically-symmetric collapse code to compute the expected conditions, instability, field growth and saturation. Akiyama *et al.* assumed initial rotation profiles, solid body or differential, invoked conservation of angular momentum on shells that should, at least, give some idea of conditions in the equatorial

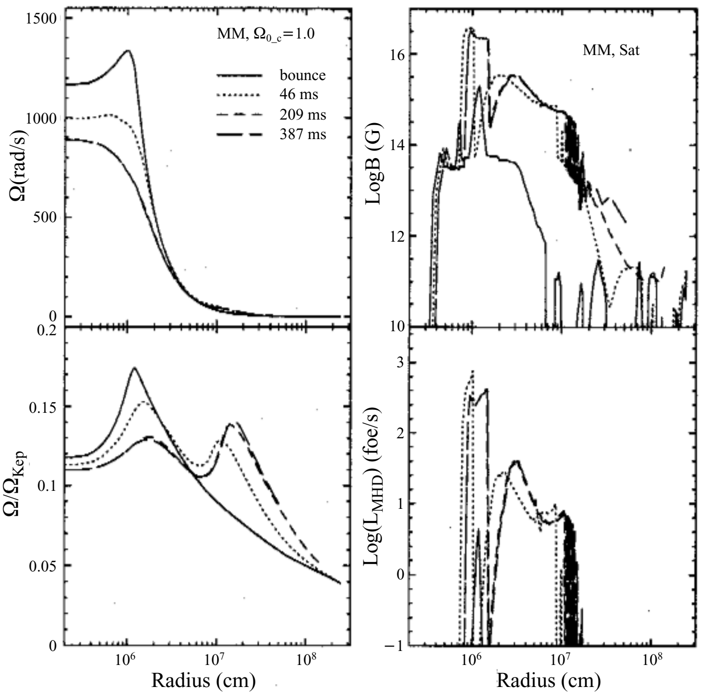


Fig. 1.1. Angular velocity, field strength and MHD luminosity (in units of $10^{51}$ erg $s^{-1}$) for a representative initial differential rotation of the iron core as a function of time from Akiyama *et al.* (2003)

plane and computed regions of MRI instability. They assumed exponential growth to saturation. For sub-Keplerian post-collapse rotation, Akiyama *et al.* found that fields can be expected to grow to $10^{15}$ to $10^{16}$ G in a few tens of milliseconds. The resulting characteristic MHD luminosity (cf. Blandford & Payne 1982) is:

$$L_{MHD} \sim B^2 r^3 \Omega/2 \sim 3 \times 10^{52} \text{ erg s}^{-1} B_{16}^2 R_{NS,6}^3 \left(\frac{P_{NS}}{10 \text{ ms}}\right)^{-1} \sim 10^{51} - 10^{52} \text{ erg s}^{-1}. \tag{1.2}$$

If this power can last for a significant fraction of a second, a supernova could result. Figure 1.1 shows the results for a model in which the iron core began with a smoothly decreasing distribution of angular velocity and a central value of $\Omega = 1$ $s^{-1}$.

The implication of the work of Akiyama *et al.* (2003) is that the MRI is unavoidable in the core collapse ambience, as pertains to either supernovae or $\gamma$-ray bursts. The field generated by the MRI must be included in any self-consistent calculation. These implications need to be explored in much greater depth, but there is at least some possibility that the MRI may lead to strong MHD jets by the magneto-rotational (Meier, Koide & Uchida 2001) or other mechanisms. A key point is that the relevant dynamics will be dictated by large, predominantly toroidal fields that are generated internally, not the product of twisting of external field lines that is the basis for so much work on MHD jet and wind mechanisms. Understanding the role of these internal toroidal fields in producing jets, in providing the ultimate dipole field strength for both ordinary pulsars and magnetars (Duncan & Thompson 1992), in setting the "initial" pulsar spin rate after the supernova dissipates (that is, the "final" spin rate from the supernova dynamicists point of view), and any connection to $\gamma$-ray bursts is in its infancy.

## 1.5 Gamma-ray bursts

We have learned so much about gamma-ray bursts since the revolution of the discovery of afterglows it is impossible to do it justice. Briefly, we now know that the energy is not spread isotropically, but is collimated into jets that seem to have a canonical energy of a few $\times 10^{50}$ ergs (Panaitescu & Kumar 2001; Frail *et al.* 2001). There is growing circumstantial evidence for a connection to massive stars, yet there is evidence that some gamma-ray bursts explode into a rather low density ISM, and little evidence in many cases for the winds that should characterize massive stars (Panaitescu & Kumar 2002).

Now we have the dramatic evidence from GRB030329/SN 2003dh (Stanek *et al.* 2003; Hjorth *et al.* 2003; Kawabata *et al.* 2003) of a definite connection between this burst and a Type Ic-like supernova. We also have the startling result of the observation by Coburn & Boggs (2003) of a large polarization, $80 \pm 20\%$ in GRB021206. One interpretation of this is that the Alfvén speed considerably exceeds the sound speed, implying a dynamically dominant field (Lyutikov, Blandford & Pariev 2003).

Despite these dramatic developments, there is much to be done. In the context of gravitational collapse models we must consider Keplerian shear, nearly equipartition fields, magnetic neutrino cross sections, strong magnetic helicity currents and viscoelastic effects (see my concluding remarks), and a host of other effects that will pertain to this rapidly rotating and inevitably magnetic environment.

One of the issues currently facing the supernova community as we grapple with the supernova/gamma-ray burst connection is whether or not there is a new class of explosions ("hypernovae," see, e.g. Maeda *et al.* 2002 and in these proceedings) or if the events we see with large photospheric velocities are just an extension of a population with a continuum of properties. There are several complications that must be borne in mind. First, the velocity at the photosphere is a very sensitive function of time for Type Ic supernovae. Just to say a velocity is "high" is not a terribly useful statement. It is the whole velocity evolution that must be compared

Table 1.1.

| EVENT | Peak $M_v$ | v at Peak (1000 km $s^{-1}$) | Ref |
|---|---|---|---|
| SN 1983V | 18.1 | 15 | (1) |
| SN 1983N | 17.4 | 10 | (2) |
| SN 1987K | 16.9 | 10 | (3) |
| SN 1987M | 18.5 | 10 | (4) |
| SN 1992ar | 19.3 | 15 | (5) |
| SN 1994I | 18.1 | 14 | (6, 7) |
| SN 1993J | 17.7 | 10 | (8) |
| SN 1997ef | 17.2 | 11 | (9) |
| SN 1998bw | 19.4 | 15 | (10, 11) |
| SN 2002ap | 17.7 | 15 | (12) |
| SN 2003dh | 20.5 | 23 | (13) |

REFERENCES – (1) Clocchiatti *et al.* (1997); (2) Clocchiatti, Wheeler, Benetti & Frueh (1996); (3) Filippenko (1988); (4) Filippenko, Porter & Sargent (1990); (5) Clocchiatti *et al.* (2000); (6) Richmond *et al.* (1996); (7) Millard *et al.* (1999); (8) Wheeler & Filippenko (1996); (9) Mazzali, Iwamoto & Nomoto (2000); (10) Galama *et al.* (1998); (11) Patat *et al.* (2001); (12) Gal-Yam, Ofek & Shemmer (2002); (13) Hjorth *et al.* (2003)

to make a valid contrast of one event with another. Even then different velocity evolution can and will result from different envelope masses without substantial differences in explosion energy. Another key factor is that we now have substantial evidence, some of it quite direct, that Type Ic supernovae are strongly asymmetric. This means that we might see different photospheric velocities in different directions (Höflich, Wheeler & Wang 1999). We can also see different luminosities in different directions. This is then related to the deduction of nickel masses, a key factor in the definition, at least in some cases, of "hypernovae." In addition, non-spherical explosions can affect the resulting density distribution and hence the gamma-ray deposition and even the late time luminosity. Since explosion energies and nickel masses are quantities derived from spherical models, great care must be taken in their interpretation when strong asymmetries are suspected.

To illustrate the empirical case, Table 1.1 gives photospheric velocity at maximum light and peak brightness for a sample of Type Ic and related supernovae for which such data were available. Whether or not a comparison at maximum light is valid or the best way to do this is not clear. The very fact that the data are sparse is a cautionary note to both advocates and critics of "hypernovae." Nevertheless, this table illustrates that Type Ic come with a considerable dispersion in both peak brightness and photospheric velocity. While it may be that SN 1998bw and SN 2003dh are especially bright, there are others as bright; and while those events may have shown high velocities, so have other Type Ic with modest peak brightness. Further data may reveal differently, but this table reveals no special pattern nor obvious bifurcation in properties between normal Type Ic supernovae and "hypernovae."

Even the great triumph of SN 2003dh has brought some new issues to the fore. The spectral evolution of SN 2003dh looks remarkably like that of SN 1998bw. How could that be since SN 2003dh was associated with a classic gamma-ray burst and must have been observed nearly down the jet axis and SN 1998bw was either associated with an odd, very subluminous gamma-ray burst, or it was seen substantially off axis. The recent report of a supernova-like spectrum in GRB 021211 by Della Valle *et al.* (2003) also adds a twist. Here again, the supernova must be seen "down the pipe," but the velocities seem to be modest. Clearly there is still much to learn about the supernova gamma-ray burst connection.

## 1.6 Conclusions

As we enter this workshop, we can point to several area of critical interest. Type Ia supernovae sometimes have significant polarization and hence asymmetry. This may yield clues to their binary origin. Perhaps we are seeing evidence of how the combustion physics proceeds. Perhaps there are hints, specifically, to the mechanism of the crucial deflagration/detonation transition.

Much hard work has also shown that all core collapse explosions are significantly polarized and hence asymmetric. This means that both the dynamics and the radiative processes (photons and neutrinos!) are asymmetric. An account of this asymmetry must be made in the analysis of core collapse.

In particular, core collapse is an intrinsically shearing environment, That makes it subject to the MRI, the resulting turbulence, and hence to strong dynamo action and the exponential growth of magnetic fields. The implication is that rotation and magnetic fields are intrinsic to the process of core collapse for either neutron stars or black holes, for supernovae or gamma-ray bursts.

Welcome to the brave new world of three-dimensional explosions!

## Acknowledgements

I am most grateful to Peter Höflich and Pawan Kumar for hosting this wonderful meeting and putting in the hard work before and after to make it scientifically successful and stimulating. I learned so much from so many colleagues over the years, but would like to especially acknowledge those who have recently led me into three-dimensional perspectives – Shizuka Akiyama, Dietrich Baade, Vadim Gamezo, Andy Howell, Alexei Khokhlov, Itamar Lichtenstadt, Dave Meier, Elaine Oran,