On the Systematics of Core–Collapse Explosions

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Abstract

Recent observations of supernovae, supernova remnants, and radio pulsars suggest that there are correlations between pulsar kicks and spins, infrared and gamma-ray line profiles, supernova polarizations, and ejecta debris fields. A framework is emerging in which explosion asymmetries play a central role. The new perspective meshes recent multi–dimensional theoretical investigations of the explosion mechanism with trends in $^{56}$Ni yields and explosion kinetic energies. These trends imply that the mass above which black holes form after collapse is $\sim 30$ $M_\odot$ and that supernova explosion energies may vary by as much as a factor of four. In addition, new neutrino–matter opacity calculations reveal that the inner cores of protoneutron stars are more transparent than hitherto suspected. This may have consequences for the delayed neutrino–driven mechanism of explosion itself. Be that as it may, as the millenium dawns a surprising array of new data and theoretical results are challenging supernova modelers as never before.

1.1 Introduction

Summarizing the important issues surrounding supernova theory is a daunting task and fraught with dangers [1, 2], but I will attempt here to highlight some of the recent developments that I find interesting and hope that the reader will be patient with the manifest limitations of this exercise. In the process, some potential systematics will be discussed and new connections between disparate classes of observations will be suggested. It is now not unreasonable to imagine a theory that unifies the spins and velocities of neutron stars, the anisotropies observed in supernova ejecta, and stellar collapse and explosion. These may be connected in a given supernova, with the debris asymmetries correlated with the kick directions and the neutrino and gravitational wave emissions related to both.

1.2 Status of Explosion Modeling

All groups that do multi–D hydrodynamic modeling of supernovae obtain vigorous convection in the semi–transparent mantle bounded by the stalled shock [3, 4, 5, 6, 8]. There is a consensus that the neutrinos drive the explosion [3] after a delay whose magnitude has yet to be determined, but that may be between 100 and 1000 milliseconds. Whether any convective motion or hydrodynamic instability is central to the explosion mechanism is not clear, with five groups [3, 4, 5, 6, 8] voting yes or maybe and one group [3] voting no. The negative vote is from a group that is taking pains to handle the transport with a minimum of approximations. However, this group opted to do the transport in 1–D, save the result, and impose this history on the 2–D calculation, without feedback. This prescription is suspect, but so are the prescriptions of all the other groups, which compromised in different ways. Hence, a definitive calculation in either two and three dimensions has not yet been performed.
It should be noted that it is not trivial to diagnose the differences between the various calculations of the major groups, nor to reproduce the algorithms they employ. In this regard, one should be cautious of facile comparisons that purport to explain the results of others. For instance, to ascribe the explosions that some groups obtain to the use of the “gray” approximation says next to nothing. There is no one “gray” approximation, though all share the dubious characteristic of not being multi–energy–group. There are many implicit spectra and spectral forms that can be assumed, various flux limiters, a variety of source terms, a number of algorithms to merge opaque and transparent regimes, different approximations for the integrals of the Pauli blocking factors, and different cross sections averages, to name only the most obvious. Furthermore, the differences between a multi–group flux–limited calculation and a full transport calculation can be larger than the differences between a well–chosen “non–gray” calculation and the latter. The range of possible sets of choices under the rubric of “non–gray” is vast and each set entails painstaking evaluation. Therein lies the major problem: it is harder to assemble a “non–gray” code that attempts to cover all the limits than to do the problem correctly. It is only in an effort to speed up the calculation that an integral approach is attempted and doing the full problem is always preferable if sufficient computational resources are available. In addition, it is more difficult to have confidence in a patchwork of approximations than to trust a code that incorporates the full equations, though poor angular, energy, and spatial zoning can severely compromise even an otherwise virtuous scheme.

1.3 Many–Body Correlations

To focus exclusively on numerical and transport matters is frequently to lose sight of the important issues. After the ultimate algorithm is implemented, the results will depend on the initial progenitor models and the microphysics, in particular the neutrino cross sections. In this regard, the recent explorations into the effects of many–body correlations on neutrino–matter opacities at high densities are germane [10, 11, 12, 13]. Though the final numbers have not yet been derived, indications are that we have been overestimating the neutral–current and the charged–current cross sections above $10^{14}$ gm cm$^{-3}$ by factors of from two to ten, depending upon density and the equation of state. The many–body corrections increase with density, decrease with temperature, and for neutral–current scattering are roughly independent of incident neutrino energy. Furthermore, the spectrum of energy transfers in neutrino scattering is considerably broadened by the interactions in the medium. An identifiable component of this broadening comes from the absorption and emission of quanta of collective modes akin to the Gamow–Teller and Giant–Dipole resonances in nuclei (zero–sound; spin sound), with Čerenkov kinematics. This implies that all scattering processes may need to be handled with the full energy redistribution formalism and that $\nu$–matter scattering at high densities can not be considered elastic. One consequence of this reevaluation is that the late–time ($\geq 500$ milliseconds) neutrino luminosities may be as much as 50% larger for more than a second than heretofore estimated. These luminosities reflect more the deep protoneutron star interiors than the early post–bounce luminosities of the outer mantle and the accretion phase. Since neutrinos drive the explosion, this may have a bearing on the specifics of the mechanism, but it is too soon to tell.
1.4 Systematics

Unfortunately, theory is not yet adequate to determine the systematics with progenitor mass of the explosion energies, residue masses, $^{56}\text{Ni}$ yields, kicks, or, in fact, almost any parameter of a real supernova explosion. Despite this, there are hints, both observational and theoretical, some of which I would like to touch on here. The gravitational binding energy ($B.E.$) exterior to a given interior mass is an increasing function of progenitor mass, ranging at 1.5 $\text{M}_\odot$ interior mass from about $10^{50}$ ergs for a 10 $\text{M}_\odot$ progenitor to as much as $3 \times 10^{51}$ ergs for a 40 $\text{M}_\odot$ progenitor [3, 14]. This large range must affect the viability of explosion and its energy. It is not unreasonable to conclude, in a very crude way, that $B.E.$ sets the scale for the supernova explosion energy. When the “available” energy exceeds the “necessary” binding energy, both very poorly defined quantities at this stage, explosion is more “likely.” However, how does the supernova, launched in the inner protoneutron star, know what binding energy it will be called upon to overcome when achieving larger radii? Since the post–bounce, pre-explosion accretion rate ($\dot{M}$) is a function of the star’s inner density profile, as is the inner $B.E.$, and since a large $\dot{M}$ seems to inhibit explosion, it may be via $\dot{M}$ that $B.E.$, at least that of the inner star, is sensed. Furthermore, a neutrino–driven explosion requires a neutrino–absorbing mass and there is more mass available in the denser core of a more massive progenitor. One might think that binding energy and absorbing mass partially compensate or that a more massive progenitor can just wait longer to explode, until its binding energy problems are buried in the protoneutron star and $\dot{M}$ has subsided. The net effect in both cases may be similar explosion energies for different progenitors, though the residue mass could be systematically higher for the more massive stars. However, if these effects do not compensate, the fact that binding energy and absorbing mass are increasing functions of progenitor mass hints that the supernova explosion energy may also be an increasing function of mass. Since $B.E.$ varies so much along the progenitor continuum, the range in the explosion energy may not be small. Curiously, the amount of $^{56}\text{Ni}$ produced explosively also depends upon the mass between the residue and the radius at which the shock temperature goes below the explosive Si–burning temperature, a radius that depends upon explosion energy. Hence, the amount of $^{56}\text{Ni}$ produced may also increase with progenitor mass. Thermonuclear energy only partially compensates for the binding energy to be overcome, the former being about $10^{50}$ ergs for every 0.1 $\text{M}_\odot$ of $^{56}\text{Ni}$ produced.

Not all $^{56}\text{Ni}$ produced need be ejected. Fallback is possible and whether there is significant fallback must depend upon the binding energy profile. Personally, I think that there is not much fallback for the lighter progenitors, perhaps for masses below 15 $\text{M}_\odot$, but that there is significant fallback for the heaviest progenitors. The transition between the two classes may be abrupt. I base this surmise on the miniscule binding energies and tenuous envelopes of the lightest massive stars and on the theoretical prejudice that the $r$–process, or some fraction of it, originates in the protoneutron winds that follow the explosion for the lightest massive stars [13]. If there were significant fallback, these winds and their products would be smothered.

If there is significant fallback, the supernova may be in jeopardy and much of the $^{56}\text{Ni}$ produced will reimplode. There may be a narrow range of progenitor mass over which the supernova is still viable, while fallback is significant and both the mass of $^{56}\text{Ni}$ ejected and the supernova energy are decreasing. Above this mass range, a black hole may form. Hence, both low–mass and high–mass supernova progenitors may have low $^{56}\text{Ni}$ yields. Recently, two Type IIP supernovae have been detected, SN1994W [17] and SN1997D [17], which have very low $^{56}\text{Ni}$ yields ($\leq 0.0026$ $\text{M}_\odot$ and $\leq 0.002$ $\text{M}_\odot$, respectively), long–duration plateaus,
and large inferred ejecta masses ($\geq 25M_\odot$). The estimated explosion energy for SN1997D is a slight $0.4 \times 10^{51}$ ergs. (SN1987A’s explosion energy was $1.5 \pm 0.5 \times 10^{51}$ ergs and its $^{56}\text{Ni}$ yield was $0.07 \ M_\odot$.) These two supernovae may reside in the fallback gap and imply that the black hole cut–off is near 30 $M_\odot$.

In sum, supernova $^{56}\text{Ni}$ yields may vary by a factor of $\sim 100$ and may peak at some intermediate progenitor mass, the supernova explosion energy may vary by a factor of $\sim 4$ and also may peak at some intermediate progenitor mass, and the black hole hole cut–off mass may be near 30 $M_\odot$. However, and importantly, whether real theoretical calculations will bear out these hinted–at systematics is as yet very unclear.

1.5 Young Supernovae and Supernova Remnants

There are many observational indications that supernova explosions are indeed aspherical. Fabry–Perot spectroscopy of the young supernova remnant Cas A, formed around 1680 A.D., reveals that its calcium, sulfur, and oxygen element distributions are clumped and have gross back–front asymmetries [18]. No simple shells are seen. Many supernova remnants, such as N132D, Cas A, E0102.2-7219, and SN0540-69.3, have systemic velocities relative to the local ISM of up to 900 km s$^{-1}$[19]. X–ray data taken by ROSAT of the Vela remnant reveal bits of shrapnel with bow shocks [20]. The supernova, SN1987A, is a case study in asphericity: 1) its X–ray, gamma–ray, and optical fluxes and light curves require that shards of the radioactive isotope $^{56}\text{Ni}$ were flung far from the core in which they were created, 2) the infrared line profiles of its oxygen, iron, cobalt, nickel, and hydrogen are ragged and show a pronounced red–blue asymmetry, 3) its light is polarized, and 4) recent Hubble Space Telescope pictures of its inner debris reveal large clumps and hint at a preferred direction [21]. Furthermore, radio pictures of the supernova SN1993J, which also has polarized optical spectral features, depict a broken shell. One of the most intriguing recent finds is the supernova SN1997X, which is a so–called Type Ic explosion. This supernova shows the greatest optical polarization of any to date (Lifan Wang, private communication). Type Ic supernovae are thought to be explosions of the bare carbon/oxygen cores of massive star progenitors stripped of their envelopes. As such, SN1997X’s large polarization implies that the inner supernova cores, and, hence, the explosions themselves, are fundamentally asymmetrical. No doubt, instabilities in the outer envelopes of supernova progenitors clump and mix debris clouds and shatter spherical shells. The observation of hydrogen deep in SN1987A’s ejecta [22] strongly suggests the work of such mantle instabilities. However, the data collectively, particularly for the heavier elements produced in the inner core, are pointing to asymmetries in the central engine of explosion itself.

1.6 Neutron Star Kicks

Strong evidence that neutron stars experience a net kick at birth has been mounting for years. In 1993 [23, 24], it was demonstrated that the pulsars are the fastest population in the galaxy ($< v > \sim 450$ km s$^{-1}$). Such speeds are far larger than can result generically from orbital motion due to birth in a binary (the “so–called” Blaauw effect). An extra “kick” is required, probably during the supernova explosion itself [23]. In the pulsar binaries, PSR J0045-7319 and PSR 1913+16, the spin axes and the orbital axes are misaligned, suggesting that the explosions that created the pulsars were not spherical [26, 27]. In fact, for the former the orbital motion seems retrograde relative to the spin [23] and the explosion may have kicked the pulsar
backwards. In addition, the orbital eccentricities of Be star/pulsar binaries are higher than one would expect from a spherical explosion, also implying an extra kick [29]. Furthermore, low–mass X–ray binaries (LMXB) are bound neutron star/low-mass star systems that would have been completely disrupted during the supernova explosion that left the neutron star, had that explosion been spherical [30]. In those few cases, a countervailing kick may have been required to keep the system bound. The kick had to act on a timescale shorter than the orbit period and the explosion orbit crossing time. Otherwise, the process would have been uselessly adiabatic. One is tempted to evoke as further proof the fact that pulsars seen around young (age \( \leq 10^4 \) years) supernova remnants are on average far from the remnant centers, but here ambiguities in the pulsar ages and distances and legitimate questions concerning the reality of many of the associations make this argument rather less convincing [31, 32]. However, the ROSAT observations of the 3700 year–old supernova remnant Puppis A show an X–ray spot that has been interpreted as its neutron star [33]. This object has a large X–ray to optical flux ratio, but no pulsations are seen. If this interpretation is legitimate, then the inferred neutron star transverse speed is \( \sim 1000 \text{ km s}^{-1} \). Interestingly, the spot is opposite to the position of the fast, oxygen–rich knots, as one might expect in some models of neutron star recoil during the supernova explosion. Whatever the correct interpretation of the Puppis A data, it is clear that many neutron stars are given a hefty extra kick at birth (though the distribution of these kicks is broad) and that it is reasonable to implicate asymmetries in the supernova explosion itself.

1.7 Theories of Kicks

Supernova theorists have determined that protoneutron star/supernova cores are indeed grossly unstable to Rayleigh–Taylor–like instabilities [3, 4, 5]. During the post–bounce delay to explosion that might last 100 to 1000 milliseconds, these cores with 100– to 200–kilometer radii are strongly convective, boiling and churning at sonic (\( \sim 3 \times 10^4 \text{ km s}^{-1} \)) speeds. Any slight asymmetry in collapse can amplify this jostling and result in vigorous kicks and torques [4, 34, 35] to the residue that can be either systematic or stochastic. Whatever the details, it would seem odd if the nascent neutron star were not left with a net recoil and spin, though whether pulsar speeds as high as 1500 km s\(^{-1}\) (cf. the Guitar Nebula) can be reached through this mechanism is unknown. Furthermore, asymmetries in the matter field may result in asymmetries in the emission of the neutrinos that carry away most of the binding energy of the neutron star. A net angular asymmetry in the neutrino radiation of only 1% would give the residue a recoil of \( \sim 300 \text{ km s}^{-1} \). Not surprisingly, many theorists have focussed on producing such a net asymmetry in the neutrino field, either evoking anisotropic accretion, exotic neutrino flavor physics, or the influence of strong magnetic fields on neutrino cross sections and transport. The latter is particularly interesting, but generally requires magnetic fields of \( 10^{14} \) to \( 10^{16} \) gauss [36], far larger than the canonical pulsar surface field of \( 10^{12} \) gauss. Perhaps, the pre–explosion convective motions themselves can generate via dynamo action the required fields. Perhaps, these fields are transient and subside to the observed fields after the agitation of the explosive phase. It would be hard to hide large fields of \( 10^{15} \) gauss in the inner core of an old neutron star, while still maintaining standard surface fields of \( 10^{12} \) gauss. In this context, it is interesting to note that surface fields as high as \( 10^{15} \) gauss are very indirectly being inferred for the so–called soft gamma repeaters [37], but these are a very small fraction of all neutron stars. If such large fields are necessary to impart, via anisotropic neutrino emission, the kicks observed, then the coincidence that Spruit & Phinney [35] note
between the fields needed to enforce slow pre-collapse rotation and those observed in pulsars after flux freezing amplification is of less significance.

Whether the kick mechanism is hydrodynamic or due to neutrino momentum, one might expect that the more massive progenitors would give birth to speedier neutron stars. More massive progenitors generally have more massive cores. If the kick mechanism relies on the anisotropic ejection of matter [34], then for a given explosion energy and degree of anisotropy we might expect the core ejecta mass and, hence, the dipole component of the ejecta momentum to be larger (“$p \sim \sqrt{2ME}$”), resulting in a larger kick. The explosion energy itself may also be larger for the more massive progenitors, enhancing the effect. If the mechanism relies on anisotropic neutrino emission, the residues of more massive progenitors are likely to be more massive and have a greater binding energy ($E_B \propto M_{NS}^2$) to radiate. Hence, for a given degree of neutrino anisotropy, the impulse and kick ($\propto E_B/M_{NS}$) would be greater. In either case, despite the primitive nature of our current understanding of kick mechanisms, given the above arguments it is not unreasonable to speculate that the heaviest massive stars might yield the fastest neutron stars.

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