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Thoughts on Core-Collapse Supernova Theory†

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Abstract. An emerging conclusion of theoretical supernova research is that the breaking of spherical symmetry may be the key to the elusive mechanism of explosion. Such explorations require state-of-the-art multi-dimensional numerical tools and significant computational resources. Despite the thousands of man-years and thousands of CPU-years devoted to date to studying the supernova mystery, both require further evolution. There are many computationally-challenging instabilities in the core, before, during, and after the launch of the shock, and a variety of multi-dimensional mechanisms are now being actively explored. These include the neutrino heating mechanism, the MHD jet mechanism, and an acoustic mechanism. The latter is the most controversial, and, as with all the contenders, requires detailed testing and scrutiny. In this paper, we analyze recent attempts to do so, and suggests methods to improve them.

Keywords. supernovae: general – radiative transfer – stars: magnetic fields – stars: neutron – neutrinos – hydrodynamics – MHD

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1. Introduction

After decades of theoretical exploration, it is now clear that the core collapse that leads to supernova explosions, and the supernovae themselves, are not spherical phenomena. During the violent dynamical sequence that gives birth to both a supernova and a neutron star (or black hole!), the core of a massive star runs a formidable gauntlet of hydrodynamic instabilities. First, the progenitor Chandrasekhar core experiences turbulent convection before collapse, ensuring density and entropy inhomogeneity at collapse. Then, the material behind the stalling bounce shock executes Rayleigh-Taylor overturn, aided later by neutrino heating from below that drives convection. The latter is boosted, if not overwhelmed, by the standing-accretion-shock instability (SASI; Blondin, Mezzacappa, & DeMarino 2003) that commences ∼100-250 milliseconds after bounce (Burrows *et al.* 2006), if there is no explosion before this, and has a frequency of from ∼20 to ∼80 Hz (Burrows *et al.* 2007a). The dominant SASI modes are $\ell = 1$ and $\ell = 2$ harmonics. Moreover, after bounce a shell below the neutrinospheres at ∼20-50 km in the inner core at a radius of ∼10-20 kilometers (km), executes convective overturn due to negative lepton (composition) gradients. It was hoped that such core convection, as well as doubly-diffusive instabilities ("neutron fingers"), could boost the neutrino luminosities that may ultimately be responsible for reenergizing the explosion. However, it has

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been shown that the numbers are not encouraging (Dessart *et al.* 2006; Bruenn & Dineva 1996).

In addition, once the shock is launched, it progresses through a layer cake of outer zones, each bounded by density discontinuities and composition jumps. When the shock traverses these regions it trips further Rayleigh-Taylor-like and Richtmyer-Meshkov instabilities. Coupling all of the above mechanisms by which symmetry can be broken with rotation and magnetic stresses will only further enrich the multi-dimensional character of the hydrodynamics. Clearly, symmetry breaking is a key feature of core collapse supernova explosions.

Recently, Burrows *et al.* (2006) and Burrows *et al.* (2007abcd) have suggested that the violent turbulence around the inner core and the late-phase pounding of this core by accretion streams excite vigorous $\ell = 1$ and $\ell = 2$ core g-modes that damp by the emission of sound. If there had been no earlier explosion by other means, in their simulations Burrows *et al.* find that approximately ~1 second after bounce this sound can be sufficient to reenergize the shock. They suggest dumping acoustic power in the inner mantle at a rate of perhaps more than 10^{50} ergs s^{-1} for many seconds can in principle lead to a supernova. The core g-mode is very aspherical and leads to an anisotropic, oftimes unipolar, explosion. However, this g-mode/acoustic mechanism is quite controversial. Is the resolution (temporal as well as spatial) adequate? Can such simulations be trusted after ~1,000,000 timesteps? Is the result code-dependent? Do other mechanisms, such as neutrino heating or MHD jets (Burrows *et al.* 2007e), trump the acoustic mechanism before it has a chance to operate?

Whatever the ultimate solution, a central theme for modern supernova theory has emerged − whatever the mechanism, be it neutrino heating, MHD jets, or acoustic (and it might be a mix of all three), the breaking of spherical symmetry is an organizing principle of the theoretical debate. This puts a premium on the development and testing of multi-physics, multi-dimensional radiation hydrodynamic and magnetohydrodynamic computational approaches and codes. This imperative, and the limitations of current computers and algorithms, are important reasons the supernova puzzle is as yet unsolved.

Recently, Marek (2007) and Marek & Janka (2008) have looked into the generation of core g-modes and have challenged some of the findings in our recent series of papers (Burrows *et al.* 2006,2007abcd) on the core-oscillation/acoustic power mechanism. While it is vitally important to scrutinize such novel and provocative ideas as the acoustic mechanism in detail and directly, we believe that these two studies fall somewhat short of adequately addressing the issues raised by our series on this topic. Below we explain our conclusions and make various observations we think are germane to the case at hand. Since the Marek (2007) work has more details on what is to be found in both works, we focus on it, though refer to each work where appropriate. Though our remarks and observations are critical of these works, they are meant merely to improve the science return of any group seeking to critically explore our provocative acoustic findings and we very much appreciate the effort expended by these researchers to seriously address, check, confirm, or refute our controversial findings.

Therefore, in this short paper, we map out some of the numerical challenges and methodologies of testing the core-oscillation hypothesis. We don't provide a systematic review of core-collapse supernova theory, such a task being beyond the scope of a short proceedings. For this, however, readers may profit from Burrows (2000) or Woosley & Janka (2005). Nevertheless, the enclosed discussion provides a snapshot of some of the current debate in supernova theory.

2. Summary Comments on a Recent Investigation into Core G-mode Oscillations

Here, we summarize some of our technical reservations about the Marek & Janka work, and then address more specific points in §3, §4, §5, and §6 below: 1) Their simulations do not extend to times after bounce when we say the core g-mode oscillations are large, but to times when we too say the excitation of such modes is minimal. Hence, they do not make the proper direct comparison, at the proper epoch; 2) They do their simulations in 1D in the central 1.6−1.7 km, which we believe artificially dampens the growth of the $\ell = 1$ core g-mode; 3) The measure they use for the presence of the mode is $\Delta P/P$, where P is the pressure, at a given internal radius. In the convective region this is a measure of the strength of turbulence and of the potential for excitation of the interior g-mode by turbulence, but is not a good measure of the presence of the core g-mode itself; and 4) Marek & Janka (2008) claim that the onset of explosion might require a small nuclear incompressibility (K), and tout a value of $K = 180$ MeV. Their model with $K = 263$ MeV does not look as promising. However, the measured value of K is 240±20 MeV, much closer to the value employed in their non-exploding model, calling into question their central conclusion. We now proceed with a more specific discussion.

3. On $\Delta P/P$ as an Imperfect Measure of the G-mode

Marek (2007) and Marek & Janka (2008) use $\Delta P/P$ to discern the presence of the core oscillation itself, with Marek & Janka (2008) focussing only on the interior 10 and 20 kilometer (km) radii and Marek (2008) including a discussion of the outer radius at 35 km as well. However, $\Delta P/P$ (as plotted at 35 km in Fig. 7 of Burrows *et al.* 2006) is a direct signature not of the core g-mode, but of the pressure fluctuations in the region between the shock and the inner core. The primary origins of these "outer" pressure fluctuations are the SASI and neutrino-driven convection, not the core oscillation. The restoring force for core g-modes is buoyancy in the inner ∼10 km, not pressure, and by using $\Delta P/P$ as a g-mode index Marek & Janka focus unduly on a subdominant modal signature. A better measure of the presence and strength of an $\ell = 1$ core g-mode might be the overlap with the eigenfunction itself, particularly in the displacement or velocity, and the identification of the countervailing motion of the inner core with the shell around it; for the $\ell = 1$ core g-mode these regions oscillate out of phase.

Nowhere in Burrows *et al.* (2006, 2007abcd) do we propose $\Delta P/P$ as a measure for the strength of the core g-mode pulsations. Rather, we use it as a measure of the pressure fluctuations at the surface of the protoneutron star near 25−35 km that can excite core g-mode oscillations in the first, weaker, phase of the excitation sequence we see (see also Goldreich & Keeley 1977; Goldreich & Kumar 1988,1990). The second phase is the more important, that of the "self-excited" oscillator during and after the onset of explosion, which in our calculations occurs more than ∼1 second after bounce. The calculations of Marek & Janka (2008) do not extend to more than ∼610 milliseconds after bounce, leaving a crucial gap of ∼400 milliseconds. At this earlier time, we too see small amplitudes for the core g-mode oscillations and they aren't yet having a significant dynamical influence (Burrows *et al.* 2007a).

Feedback ("extra") pressure waves from the resultant g-mode core motion are not so manifest early on at radii of ∼35−50 km, and certainly not at 10−20 km, even when the amplitude of the $\ell = 1$ core g-mode oscillation (better measured with the Lagrangian displacement in the inner 10 km) is modest, not small. g-modes are predominantly "gravity modes" and the p-mode character they have in the outer region is because of their *mixed*

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character and is sub-dominant. It is only when the core oscillation becomes *non-linear* that the p-mode character of the outer region of the core g-mode becomes interesting. Then, the outer pressure wave components of the *complex* g-mode can propagate out with vigor and steepen into shocks. All during this time the inner 10 km (with a node near 6−8 km) is oscillating in g-mode fashion, with gravitation/buoyancy as the restoring force. Note that this inner region is not convective and the inner g-mode is not, of course, in an evanescent region, though its outer tail is; it is only there in the evanescent region that the mode is predominantly p-mode in character. This is quite unexceptional (Unno *et al.* 1989).

In our simulations, supersonic accretion funnels that penetrate through the kinks in the outer shock structure created by the vigorous SASI are the ultimate agents of strong core g-mode excitation. It is the downflowing plumes and their *ram pressure* that excite the $\ell = 1$ core g-mode at very late times. Even when these accretion funnels are steadily impinging upon the inner core and do not have resonant frequency components, they can excite ∼300-Hz g-modes; witness the generation of gravity waves on a pond due to a steady jet of water. It is the width of the exciting stream, not its temporal fluctuation, that sets the "wavelength" of the g-modes that can be excited. The frequency spectrum of the excitation is a consequence of this wavelength and the dispersion relation of gravity waves on the inner core. This excitation frequency spectrum easily overlaps the core g-mode spectrum.

4. On the Amplitudes of $\Delta P/P$

$\Delta P/P$ and Mach number in post-shock regions grow with time in models for which the shock is stalled and it bounds the inner turbulent region. This includes almost all models published to date. Mach numbers approach a few tenths to ∼0.5 at late times (0.5-1.0 seconds). The Mach numbers provide a measure of the vigor of the motions in this region. In turbulent regions, high Mach numbers translate directly into high pressure fluctuations, with Mach numbers near one implying pressure fluctuations of order unity, i.e. large.

It is not clear why in the calculations of Marek (2007) $\Delta P/P$ in the turbulent regions is generically small, even at the latest times achieved (for most of his models, around ∼350 milliseconds after bounce). Both Burrows *et al.* (2006, 2007abc) and Yoshida, Ohnishi, & Yamada (2007) have published much larger values that seem more consistent with the character of the late post-shock turbulent flow. As noted, Marek (2007) generally does not simulate long enough after bounce. Also, his initial seed perturbations might be small. With small seeds it takes longer to erase the memory of initial conditions and to achieve a given amplitude. During ∼0.05 to ∼0.5 seconds after bounce, Yoshida, Ohnishi, & Yamada obtain values of $< \Delta P/P >$ for the $\ell = 1$ component near 35 km of ~ 0.1, with excursions to 0.2. For this same quantity, Burrows *et al.* (2006) see a steady growth in its value from ∼0.05 at 0.3 seconds after bounce to ∼0.2 at ∼0.55 seconds after bounce. However, Marek (2007) obtains values of $\Delta P/P$ for the $\ell = 1$ component at r =35 km and at ∼350 ms after bounce of only ∼0.005 to 0.02. Interestingly, the value Marek obtains depends upon the EOS employed (see Marek 2007, Figures 5.9 and 5.10), with ten times larger amplitudes for the softer EOS. Marek & Janka (2008) do calculate one model to ∼610 ms after bounce, but this model is rotating modestly and rotation is expected to partially suppress the SASI implicated in the turbulence generated in this region (Burrows *et al.* 2007a). Nevertheless, even in this model $< \Delta P/P >$ achieves a value of ∼0.05 and is still rising when it is halted. In fact, $< \Delta P/P >$ is rising at the end of all the Marek (2007) simulations. To directly compare the values of $\Delta P/P$ in the outer turbulent regions and the g-mode amplitudes in the inner core with those Burrows *et al.* (2007abc) obtain, it is important for Marek & Janka to continue their simulations for another $\sim$500 ms. In Burrows *et al.* (2007a), we needed to evolve for more than 0.9−1.0 seconds to see vigorous core g-mode oscillation. It takes a long time for the core oscillation to manifest itself and the simulation time needs to be commensurate.

5. On Simulating the G-mode

To show that the MPA hydro code can support and simulate $\ell = 1$ g-modes, Marek (2007) calculates a few test models in which he imposes such a mode in the inner core and follows it for $10 - 20$ milliseconds. Ten to twenty milliseconds is only a few oscillation cycles. However, in all but one model, he constrains the inner 1.6 km to 1D motion. In Marek & Janka (2008), this constrained inner core has a radius of 1.7 km. The g-mode is, thereby, forced to flow *around* this inner 1.6/1.7 km. Since the node of this mode is near 6−8 km, we believe that 1.6 km is too large a region in which to inhibit the necessary multi-D flow. Importantly, the $\ell = 1$ g-mode has its greatest amplitude in this central region, where its eigenmode motion is straight through $r = 0$ (the modal velocities are the same for $+x$ and $-x$; spherical coordinates with a reflecting boundary at $r = 0$ unphysically flip the sign, by construction). Though in Marek (2007) and Marek & Janka's (2008) 2D/1D calculations the pressures and velocities are fluctuating around this 1.6/1.7-km region, the implied constraint force that keeps the very inner core from naturally responding will by its nature mute the expression of the $\ell = 1$ g-mode.

In the calculation reported by Marek & Janka (2008), they see the imposed g-mode oscillation decay within a few cycles, which is rather fast. They state in reference to their tests: "These demonstrate that our code is well able to track large-amplitude g-modes, also of dipole character, *if such modes are excited in the neutron star core* [our italics]." However, they do not in fact demonstrate that their code can track in a self-consistent fashion *long-term* excitation by anisotropic accretion and turbulence. This is the crucial question and they have not shown that their inner 1D region doesn't inhibit excitation. The decay they witness could easily be due in part or in large measure to the fact that their inner core is anchored. One way to address this would be to explore the dependence of the decay time on the size of the region that one does in 1D. For this test, the radius of the 1D region could be varied from, say, 0.5 km to 4 km.

Marek (2007) does indeed perform one test calculation all the way to the center ($r = 0$), and presumably imposes a reflecting boundary condition there. However, he calculates this model for a total of only $\sim$10 ms and starts the calculation only $\sim$30 ms after bounce. As seen in Burrows *et al.* (2006, 2007a), this is far too early to start and far too short a time to perform such a calculation if one wants to witness the excitation of core oscillations. Hence, by constraining the inner 1.6 km or employing a reflecting boundary at $r = 0$, the most important and largest amplitude region of the $\ell = 1$ mode is thereby neutered and its excitation inhibited. To clearly avoid this problem, we believe that simulations should be done with a quasi-Cartesian grid at the very center. Otherwise, the amplitude of the g-mode seen in a given hydrodynamic environment is artificially suppressed. This fact and our experience are the origins of our caveats in Burrows *et al.* (2006, 2007ab).

6. Additional Observations

Marek (2007) claims that the acoustic-driven explosions seen in the simulations of Burrows *et al.* (2006, 2007ab) arise rather abruptly. However, in fact, these explosions emerge in those simulations over a period of ~100-200 ms. For comparison, when a neutrino-driven explosion is witnessed in the calculations of Buras *et al.* (2006), Kitaura *et al.* (2006), or Burrows et al. 2007c, it emerges on a timescale of ~50-150 ms. We suggest that this is a characteristic timescale for any explosive instability in the "supernova" core and that the acoustic mechanism is not exceptional in this regard. Marek (2007) also claims that at the late times when Burrows *et al.* (2006, 2007ab) see vigorous core oscillations there is not sufficient accretion power to maintain it. As Figures 2 and 7 in Burrows *et al.* (2007a) clearly show, though the accretion rate has subsided by these times, there is still ample accretion power to maintain such oscillations. It is merely a matter of the efficiency of the conversion of accretion power into mechanical power, as opposed to neutrino luminosity. A ~10% efficiency would be adequate for this purpose.

Marek (2007) suggests that when the shock radius achieves a value larger than ~300 km this indicates the onset of explosion, that this is a "point of no return." The calculations of Marek (2007) and Marek & Janka (2008) are stopped near the time when the average shock radius achieves this value, though why is not clear. Marek & Janka (2008) add in the discussion of their results the timescale τ_{adv} versus τ_{heat} condition advocated by Thompson, Quataert, & Burrows (2005), but such arguments are no substitute for actual calculation. During the vigorous SASI phase, it is often the case that the shock radius substantially exceeds 300 km, only to recede again and continue non-linear and bounded SASI pulsation (Burrows *et al.* 2006, 2007a). Hence, we caution against using simple criteria for the onset of explosion. In fact, none of the SASI- and neutrino-aided "explosions" seen by the MPA group, neither the 11.2 $M_{\odot}$ model of Buras *et al.* (2006) nor the 15 $M_{\odot}$ model of Marek & Janka (2008), is actually followed for more than a few tens of *milliseconds* after explosion seems to ensue. It is crucially important that any claim of explosion be buttressed by calculations in which the shock actually achieves a radius of thousands of kilometers (preferably larger), and not just 300-400 km. The calculations of Burrows *et al.* (2006, 2007abcd) were carried out until the shock reached a radius of 4000-5000 km, and even this should not be considered far enough.

Importantly, we note that the incompressibility (K) of nuclear matter has been measured to be 240±20 MeV (Shlomo, Kolomietz, & Colò 2006; Lattimer & Prakash 2007). Marek & Janka (2008) calculate models using values of 180 MeV and 263 MeV, and conclude that only the 180-MeV model witnesses the onset of explosion. As a result, it is not clear, given the dependence on the EOS they identify in their calculations, that a more realistic value of K would lead to the same explosive behavior they claim for their model with $K = 180$ MeV.

In conclusion, we do not challenge the possibility that the neutrino mechanism might act on shorter timescales than the acoustic mechanism, and thereby abort it. However, we do hope that the community will redouble its efforts to test in a cogent and clear fashion its particulars and viability. This will require calculations to at least 1.2 seconds after bounce and the demonstration that these calculations do not suppress $\ell = 1$ and $\ell = 2$ core g-mode oscillations due to numerical exigencies. Conversely, we are redoubling our efforts to address afresh all the issues that attend core-collapse theory, including the neutrino, acoustic, and MHD mechanisms in all their particulars (see, for example, Dessart *et al.* 2007,2008; Hubeny & Burrows 2007; and Burrows *et al.* 2007e).

References

Blondin, J. M., Mezzacappa, A., & DeMarino, C. 2003, *ApJ*, 584, 971
Bruenn, S. W. & Dineva, T. 1996, *ApJ*, 458, L71
Buras, R., Janka, H.-T., Rampp, M., & Kifonidis, K. 2006, *A&A*, 457, 281

Burrows, A. 2000, *Nature*, 403, 727
Burrows, A., Dessart, L., & Livne, E. 2007c, in: R. McCray, K. Weiler, & S. Immler (eds.), *SUPERNOVA 1987A: 20 YEARS AFTER: Supernovae and Gamma-Ray Bursters* (New York: AIP) *AIP Conf. Proc.*, 937, 370
Burrows, A., Dessart, L., Livne, E., & Ott, C. D. 2007b, in: G. E. Brown (ed.), *Centennial Festschrift for Hans Bethe*, (Netherlands: Elsevier), *Phys. Rep.*, 442, 23
Burrows, A., Dessart, L., Livne, E., & Ott, C. D. 2007d, in: L. A. Antonelli, G. L. Israel, L. Piersanti, L., & A. Tornambe (eds.), *The Multicoloured Landscape of Compact Objects and their Explosive Origins* (New York: AIP), *AIP Conf. Proc.*, 924, 243
Burrows, A., Livne, E., Dessart, L., *et al.* 2006, *ApJ*, 640, 878
Burrows, A., Livne, E., Dessart, L., *et al.* 2007a, *ApJ*, 655, 416
Burrows, A., Dessart, L., Livne, E., *et al.* 2007e, *ApJ*, 664, 416
Dessart, L., Burrows, A., Livne, E., & Ott, C. D. 2006, *ApJ*, 645, 534
Dessart, L., Burrows, A., Livne, E., & Ott, C. D. 2007, *ApJ*, 669, 585
Dessart, L., Burrows, A., Livne, E., & Ott, C. D. 2008, *ApJ*, 673, L43
Goldreich, P. & Keeley, D. A. 1977, *ApJ*, 212, 243
Goldreich, P. & Kumar, P. 1988, *ApJ*, 326, 462
Goldreich, P. & Kumar, P. 1990, *ApJ*, 363, 694
Hubeny, I. & Burrows, A. 2007, *ApJ*, 659, 1458
Kitaura, F. S., Janka, H.-T., & Hillebrandt, W. 2006, *A&A*, 450, 345
Lattimer, J. M. & Prakash, M. 2007, *Phys. Rep.*, 442, 109
Marek, A. 2007, Ph. D. Thesis, Technical University of Munich (http://mediatum2.ub.tum.de/doc/604499/document.pdf)
Marek, A. & Janka, H.-T. 2008, *ApJ* submitted (arXiv:0708.3372)
Shlomo, S,, Kolomietz, V. M., & Colò, G. 2006, *Eur. Phys. J.*, A30, 23
Thompson, T. A., Quataert, E., & Burrows, A. 2005, *ApJ*, 620, 861
Unno, W., Osaki, Y., Hiroyasu, A., *et al.* 1989, *Nonradial oscillations of stars, 2nd ed.* (Tokyo: University of Tokyo Press)
Woosley, S. E. & Janka, H.-T. 2005, *Nature Physics*, 1, 147
Yoshida, S., Ohnishi, N., & Yamada, S. 2007, *ApJ*, 665, 1268

Discussion

Stanek: Theorists fail to make core-collapse SNe. Does nature ever fail to make a SN from a massive star? Wht are the observational constraints?

Burrows: I think that SN rates, OB star birth rates, pulsar birth rates, and nucleosynthetic constraints suggest that most massive stars must 'supernova', though a factor of two difference is still possible. However, I know of no compelling reason 'success' and 'failure' should alternate or vary wildly along the mass function. I don't think rotation is a key ingredient of explosion, except for hypernova and perhaps GRBs, rare subsets of the massive star family outcomes, so this parameter does not provide an acceptable out.

Limongi: One of the most important issues for masive stars is their final fate. Many people refer to the WHW or our picture, but in my opinion all the pictures must be taken very carefully because they have been obtained with simulated explosions that suffer many uncertainties. For how long can you perform your computations and can you say what is the real fate of a massive star at least in some cases?

Burrows: We calculate for approximately 1-1.5 seconds of physical time after core bounce. While this is quite long by the standards of the field, it is not long enough to determine much of what we would like to know, such as final explosion energy, kick velocity, matter fallback, or the r-process. For the least-massive massive stars (8-9 $M_\odot$) we think we can conclude they are underenergetic (a few 10^{50} ergs), but much of what

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we want and need to know about the fate of a generic massive star is currently beyond credible theory, alas.

Modjaz: Would an observational signature/prediction for your new acoustic SN mechanism be that the SN are unipolar, not bipolar? So, for example, polarization measurements of SN Ib/c could test that by constraining the geometry (bipolar vs. unipolar).

Burrows: Yes, more often than not I would expect acoustic-driven explosions to be top-bottom asymmetric. However, late-time neutron-driven explosions, of all but the least-massive massive stars, should also be top-bottom asymmetric and slightly unipolar. So, 'unipolar' vs. 'bipolar' is a means of distinguishing MHD-driven jet models of explosion from both acoustic and neutron models. To distinguish acoustic and many neutrino driven models from one another via morphology or polarization requires more subtle discriminants.

Davidson: This is a little off the track of your main concerns, but those lovely graphics make it irresistible. Of course you have shown some impeccable jets, but do cannonballs ever occur? The Crab Nebula includes a line of very well separated, dense, compact ovoidal things, which MacAlpine called 'argoknots' for reasons you can guess. Morphologically they are astounding.

Burrows: We do not get sprays and clumps of material, but instabilities in the star and circumstellar material due to the passage and progress of the shock and later cooling are more likely culprits. However, the explosion asymmetry we see certainly set the stage for the variegated structures and condensations that emerge and are captured in SNR images.

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