Synthetic Spectra from 3D Models of Supernovae

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Abstract. We describe Brute, a code for generating synthetic spectra from 3D supernova models. It is based on a Monte Carlo implementation of the Sobolev approximation. The current version is highly parameterized, but in the future it will be extended for full NLTE spectrum modelling of supernovae.

1. Introduction

The amount of evidence that the envelopes of supernovae (SNe) can deviate from spherical symmetry is increasing. Net intrinsic polarization measurements from some SNe are consistent with ellipsoidal envelopes (Howell et al. 2001; Leonard et al. 2001; Leonard et al. 2000; Wang et al. 2001; Wang et al. 1997; see Wheeler 2000 for a list of measurements). In some flux spectra, a clumpy or macroscopically mixed ejecta distribution (or at least a nonspherical excitation structure) has been invoked to explain phenomena such as the “Bochum event” in SN 1987A (Phillips & Heathcote 1989; Utrobin, Chugai & Andronova 1995). Most conspicuously, the interesting morphologies of SN remnants may indicate macroscopic mixing in the initial SN envelopes (Decourchelle et al. 2001; Fesen & Gunderson 1996; Hwang, Holt & Petre 2000; Tsunemi, Miyama & Aschenbach 1995). These findings have inspired new 3D explosion models (Khokhlov 2000; Reinecke, Hillebrandt & Niemeyer 2002; Kifonidis et al. 2000). Testing new models as they arise will require detailed NLTE radiative transfer calculations in 3D.

Nonetheless, considering and deducing general constraints on SN geometry without such detailed calculations can be fruitful (Thomas et al. 2002). We have developed a parameterized synthetic spectrum code for 3D models of SNe called Brute which we describe here. In §2 we describe the assumptions and implementation of Brute, and in §3 we outline future work to bring the code toward a detailed analysis code.

2. Model

Brute was designed under some of the same basic assumptions as the highly successful direct analysis code Synow (Fisher 2000; Deng et al. 2000; Millard et al. 1999). Both codes use a simplified model of a SN atmosphere which has been called the “elementary supernova” (ES; Jeffery & Branch 1990). The major difference is that Synow is a strictly 1D code, but Brute is for arbitrary geometry.
2.1. The Elementary Supernova Model

The ES model is a simplified picture of a SN at phases between a few days to a few months after explosion. It consists of a central, optically thick continuum-emitting core surrounded by an extended envelope within which line formation occurs. The SN expands homologously so that $v \propto r$ for all matter elements.

The ES core (or photosphere) is approximated by a surface which emits blackbody radiation at some specified temperature. The photosphere is sharp, meaning that all radiation regardless of wavelength originates at the same physical surface.

Radiation transfer in the envelope is accomplished by means of the Sobolev approximation (Sobolev 1947; Rybicki & Hummer 1978), justified in detail for the SN case by Jeffery & Branch (1990). The assumption of homologous expansion provides a great simplification in the calculations, because then (1) Sobolev optical depth is angle independent, (2) common point velocity surfaces for intensity integrals are spheres and (3) propagating photons only redshift with respect to the matter and never blueshift. For each ion used in the envelope, the optical depth of a “reference line” is parameterized spatially using a contrast function. All other line optical depths of the same ion are scaled assuming LTE. The source function is taken to be that of pure resonance scattering ($S = J$).

It should be noted that the parameterized prescription here can be replaced by one with more detail. The resonance scattering assumption can be generalized as well. The effects of special relativity in the transfer can be included (to minor effect; Jeffery 1993). Electron scattering also may be included. To speed up transfer, lines close together in wavelength can be grouped into bands of small width to prevent needless extra calculations. For the purpose of direct analysis of SN spectra however, the above parameterized prescription is sufficient.

Once the source function has been determined for each line at all points in the envelope, a formal solution along impact parameter beams toward an observer is calculated. Again, the Sobolev approximation simplifies this process, since emission in a given wavelength from the SN arises only from common direction velocity planes perpendicular to the line of sight.

2.2. 3D Implementation

The key difference between the 1D and 3D implementation is the method by which the mean intensity is calculated. In 1D, we can take advantage of an azimuthal symmetry in the intensity arriving at a point to simplify the mean intensity integral. But in 3D, such symmetry is missing and the integral becomes more problematic. To avoid this problem, we adopt a Monte Carlo approach, based largely on 1D codes (Abbott & Lucy 1985; Mazzali & Lucy 1993; Mazzali 2000).

Packets of equal energy with wavelengths drawn from the Planck distribution are emitted from the surface of the core such that the core is a Lambert radiator. The packet random walks from line scattering to line scattering as it redshifts into resonance with lines of increasing wavelength. The probability that a packet undergoes a scattering (coherent in the comoving frame) is determined by the optical depth at the resonance targets.

As each packet enters a new cell of the envelope or immediately after a scattering, an “event” optical depth is chosen to “schedule” the next possible
scattering: $\tau_{\text{ev}} = -\ln(R)$ where $R$ is a random number between 0 and 1. As the packet propagates through the cell, it accumulates optical depth from the lines it encounters until the total exceeds $\tau_{\text{ev}}$. The packet then scatters coherently.

From the perspective of a single cell in the envelope during a simulation, packets of equal energy intersect the cell from many directions. The locus of points defined by the packets’ previous resonance targets form the common point velocity surfaces. The Monte Carlo technique assembles these surfaces implicitly. The radiation field is built up by counting packets that come into resonance with lines everywhere in the envelope. At the end of the simulation, the total luminosity is used to calibrate the weight of a single packet, converting the packet-in-resonance tallies into estimates of $J$ in each line.

Of course in 3D, the appearance of a spectrum may depend on the line of sight to the envelope. Rather than wait for enough packets to emerge along all lines of sight (a serious problem), we employ the same formal integral technique used in the 1D calculation. Once the source function is determined everywhere by Monte Carlo, common direction plane positions are computed and the flux is integrated across impact parameter beams. This technique greatly reduces the number of packets to follow in a simulation.

3. Future work

In order to resolve variations in optical depth that are small in size, the resolution of the envelope must be increased. The simplest solution is to use a big computer with a lot of memory, or split the envelope up amongst multiple processors. The fact that we need only sweep the line list from blue to red may help, and we can load segments of the line list as the calculation progresses.

Including electron scattering in the calculations, and replacing the assumption of pure resonance scattering with branching will help to make the code more consistent overall. The eventual goal is a NLTE code for use with new 3D explosion models. Until the reliability and quantity of those models increases,
a great deal about deviations from spherical symmetry in SNe can be learned from a parameterized code.

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References

Abbott, D., Lucy, L. 1985 ApJ 288, 679
Decourchelle, A., et al. 2001 A&A 365, L218
Deng, J., Qiu, Y., Hu, J., Hatano, K., Branch, D. 2000 ApJ 540, 452
Fesen, R., Gunderson, K. 1996 ApJ 470, 967
Fisher, A. 2000 PhD Thesis, U of Oklahoma
Reinecke, M., Hillebrandt, W., Niemeyer, J. 2002 A&A in press, also astro-ph/0206459
Howell, D., Hoflich, P., Wang, L., Wheeler, J. 2001 ApJ 556, 302
Hwang, U., Holt, S., Petre, R. 2000 ApJ 537, L119
Jeffery, D. 1993 ApJ 415, 734
Jeffery, D., Branch, D. 1990, in Supernovae, Jerusalem Winter School for Theoretical Physics, ed. J. C. Wheeler, T. Piran & S. Weinberg (Singapore: World Scientific), 149
Khokhlov, A. 2001 ApJ in press, astro-ph/0008463
Kifonidis, K., Plewa, T., Janka, H.-Th., Muller, E. 2000 ApJ 531, L123
Leonard, D., Filippenko, A., Ardila, D., Brotherton, M. 2001 ApJ 553, 861
Leonard, D., Filippenko, A., Barth, A., Matheson, T. 2000 ApJ 536, 239
Mazzali, P. 2000 A&A 363, 705
Mazzali, P., Lucy, L. 1993 A&A 279, 447
Millard, J., et al. 1999 ApJ 527, 746
Phillips, M., Heathcote, S. 1989 PASP 101, 137
Rybicki, G., Hummer, D. 1978 ApJ 219, 654
Sobolev, V. 1947 Moving Envelopes of Stars (Leningrad: Leningrad State UP) (English transl. S. Gaposchkin [Cambridge: Harvard UP, 1960])
Thomas, R., Kasen, D., Branch, D., Baron, E., 2002 ApJ 567, 1037
Tsunemi, H., Miyata, E., Aschenbach, B. 1999 PASJ 51, 711
Utrobin, V., Chugai, N., Andronova, A. 1995, A&A 295, 129
Wang, L., Howell, D., Hoflich, P., Wheeler, J. 2001 ApJ 550, 1030
Wang, L., Wheeler, J., Hoflich, P. 1997 ApJ 476, L27
Wheeler, H., 2000 in Cosmic Explosions, ed. S. S. Holt & W. W. Zhang (New York : AIP), 445; also astro-ph/9912403