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Synthetic Spectrum Methods for Three-Dimensional Supernova Models

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Current observations stimulate the production of fully three-dimensional explosion models, which in turn motivates three-dimensional spectrum synthesis for supernova atmospheres. We briefly discuss techniques adapted to address the latter problem, and consider some fundamentals of line formation in supernovae without recourse to spherical symmetry. Direct and detailed extensions of the technique are discussed, and future work is outlined.

1.1 Introduction

Spectrum synthesis is the acid test of supernova modelling. Unless synthetic spectra calculated from a hydrodynamical stellar explosion model agree with observations, the model is not descriptive. Some explosion modellers contend that only three-dimensional (3D) models faithfully describe the physics of the real events. If this is so, then the evaluation of those models requires solutions to the 3D model supernova atmosphere problem. These solutions require full detail, the inclusion of as much radiation transfer physics as possible. Otherwise, a bad fit of a synthetic spectrum to an observed one might have less to do with the accuracy of the hydrodynamical model, and more to do with the shortcomings of the radiation transfer procedure.

On the other hand, solutions (of a sort) to the ill-posed inverse problem constrain parameter space available to hydrodynamical models. Fast, iterative, parameterized fits to observed spectra characterize the ejection velocities and identities of species found in the line forming region. Most importantly, the procedure reveals species that cannot be identified by simply Doppler-shifting line lists on top of observed spectra in search of feature coincidences. Generalizing this direct analysis technique to 3D is key to constraining the geometries of real explosions.

This proceedings contribution briefly describes some steps toward the
complimentary goals of detailed and direct analysis in 3D, with an emphasis on pedagogy. For an in-depth application of the more detailed technique, refer to the contribution of D. Kasen.

1.2 Approach
Work underway to extend spherically symmetric non-LTE modelling codes to 3D could take the better part of a decade. An alternative approach, which yields a direct analysis code along the way, is to begin with a simple 3D code and augment its physics details. The ultimate goal is complete non-LTE radiation transfer in 3D with full and realistic treatment of the boundary conditions at depth. This means that the evolution of radiation from deposition to escape is modelled without the central “light bulb” approach.

We embark on the journey toward full 3D non-LTE modelling from the elegant and humble shores of the Sobolev method ([Castor 1970; Rybicki & Hummer 1978]). The Sobolev method greatly reduces the scale of the wavelength-domain of the problem by approximating line transfer, but does so at an accuracy cost. When faced with the alternative, some inaccuracy in the line transfer is acceptable. Full solutions to the 3D radiation transfer problem are simply not possible yet, so the limited inaccuracies (and the awareness of them) seems a small price to pay for progress.

The particular implementation of the Sobolev method is the Monte Carlo technique, based largely on the formalism described primarily by L. Lucy in a series of papers (e.g., [Lucy 1999]). The key innovation described in those papers we call the equal-energy packet (EEP) technique. In the EEP picture, individual photon trajectories are not simulated, but rather monochromatic photon packets of equal energy propagate through the model atmosphere. This paradigm obviates recursive trajectory calculations which make development and extension of transfer codes difficult. Of course, the scalability of the Monte Carlo technique is one of its greatest virtues. Provided the model atmosphere need not be split up across distributed nodes, communication proves almost nonexistent. Most importantly, this implementation micro-manages the energy conservation (flux divergence-less-ness) of the radiation field at all positions (or depths). Scattering is coherent in the comoving frame. Absorption and re-emission is accomplished through roulette-wheel selection (producing either a simple equivalent two-level atom or non-LTE source function). The Monte Carlo algorithm propagates variations in the radiation field instantaneously (provided enough packets are used), and this makes a simple Λ-iteration work.
Clearly, waiting for enough packets to exit the model atmosphere in any given direction of interest is not the most efficient use of limited computer time. Hence, at least for flux spectra, we can easily use the packets to establish the radiation field (energy density) throughout the envelope. From that, we derive the source function at all points and compute the emergent spectrum for any line of sight, a kind of “formal integral,” again simplified by the Sobolev approximation. This technique greatly reduces the number of packets required to build a spectrum.

Other extensions to the method besides the formal integral for emergent spectra include polarized transfer and a way of treating energy deposition from radioactive decay in the ejecta. The propagation of Monte Carlo Stokes vectors for computing polarization spectra and progress away from the central “light bulb” approximation are exemplified in D. Kasen’s contribution.

1.3 Simple Constraints on Nonsphericity

The starting question is a rather obvious one, but its answer is fundamental. If deviations from spherical symmetry occur in supernova atmospheres, what is the corresponding detection threshold for their evidence to appear in flux spectra? The changes to line profiles resulting from nonsphericity are easy to understand, but we seek means of quantitatively exploiting the results to constrain supernova geometry.

To find out, we conduct a very simple experiment. We generate a series of distributions of Sobolev optical depth covering a range of nonsphericity scales. For each model, we compute line profiles from a large number of lines of sight. This gives us a sense of what sort of diversity can be generated by what size of perturbation. In Figure 1.1 are line and covering fraction profiles averaged over 100 lines of sight. The scatter around the average is summarized by a 1-σ deviation from the average. The covering fraction for a given velocity is defined as the fraction of the projected photosphere surface obscured by Sobolev optical depth exceeding 1. We deduce three facts from the results. First, nonsphericity of the kind considered here can most strongly influence absorption features. Second, these nonsphericities only weakly influence emission features. (Both of these previous points are reversed if the line source function significantly exceeds that of resonance scattering).

Third and most importantly, the diversity trend as a function of the line of sight is directly correlated with the photospheric covering fraction. Hence, it is possible to suggest a threshold scale of clumpiness below which clumping
goes undetected in flux spectra. At first this result seems purely academic, since nature presents us with only one line of sight to a given supernova. However, we can apply the result to make a claim about models for spectroscopically normal Type Ia supernovae. Such supernovae are spectroscopically homogeneous, and we find that the depth of the Si II feature in these events is a fairly repeatable 0.7 times the local continuum. In fact, the measured scatter seems to suggest that perturbations like those explored here must be smaller than 10% the size of the photosphere area if they are indeed present. More importantly, if pure 3D deflagrations exhibit such large scale perturbations leading to wildly fluctuating line covering fractions as a function of perspective, they cannot account for such events.

1.4 Direct Analysis in 3D

The oft-repeated goals of spherically symmetric direct analysis are to identify lines and velocity intervals within the line forming region where the parent ions of those lines are found. In direct analysis, special attention is given to treating line blending, since this is an important feature of supernova spectra. Without this attention, we have seen that identifications are problematic, and these problems make it more difficult to narrow down the range of hydrodynamical models that are worth pursuing.

To provide the same direct analysis capabilities, but without recourse to spherical symmetry, we developed a code called Brute, based on the earlier,
spherically symmetric (and non-Monte Carlo) code Synow. The basic picture is the same, except that instead of radial functions of Sobolev optical depth in a reference line of each ion included, we use a template (constructed in any fashion) that need not be spherically symmetric.

An application of this code to the unique Type Ia supernova 2000cx appears in Thomas et al. (2003). The maximum light spectra of this object exhibited unusual, narrow high-velocity features, particularly in the Ca II infrared triplet. Using alternate 1D and 3D models of optical depth in Ca II, we find that partial blocking of the photosphere by a nonspherical ejecta distribution can help explain some of these features. Simultaneous fits are attempted to the corresponding Ca II UV feature, and we find that the 3D distribution is less problematic than the 1D one. The origin of the high-velocity material in this supernova is still a mystery, but how much of the observed diversity in these objects is due to 3D distributions of ejecta at high velocity? More modelling of more objects is needed.

1.5 Detailed Analysis in 3D

A special characteristic of the Monte Carlo technique is that it allows for simple solution to the radiative equilibrium problem. This permits more self-consistent modelling of emergent spectra from real hydrodynamical models. Given a composition and density structure (in any geometry), we use the $\Lambda$-iteration procedure to construct self-consistent temperature structures.

In Figure 1.3 temperature structures and spectra are shown from 10 iterations to a converged model. Though this particular model is spherically symmetric (a W7-like model mixed above 9000 km s$^{-1}$), the convergence
speed is striking. This provides us with hope that (at least for now) we can begin modelling real hydrodynamical explosion models, at least in LTE.

1.6 Conclusion

The path to fully detailed 3D non-LTE spectrum synthesis for supernova models is clear. Including non-LTE and continuum transfer effects will permit us to examine core collapse supernovae more closely, to help unlock the connection between supernovae and gamma-ray bursts. The eventual goal of dispensing with the Sobolev approximation will also be reached, and progress is already underway with realistic lower boundary conditions and gamma-ray transport.

Eventually, 3D hydrodynamical stellar explosion models will be carried to the homologous expansion phase. Those models will be converted into flux and polarization spectra to be compared with observations. Until then, there is much computer time to be burned.

This work is supported by grant HST-AR-09544-01.A, provided by NASA through the STScI, operated by the AURA, Inc., under NASA contract NAS5-26555.

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