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Line profiles as diagnostics in supernova envelopes

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Abstract. A variety of profiles of both absorption and emission lines is discussed to exemplify the sort of information one can glean of the physical state of the expanding envelope or of circumstellar material in the vicinity of the supernovae (SN). To be used in a quantitative fashion these profiles generally need to have good signal/noise and a time series is quite often helpful in testing the validity of their interpretation.

Key words. Stars: abundances – Supernovae: Envelopes – Supernovae: Absorption – Supernovae: Emission – Supernovae: circumstellar

1. Introduction

Profiles of both absorption and emission lines formed in or near the moving envelope of a SN offer valuable information on the physical state of the envelope and the surrounding material with which it interacts. Before presenting various examples it is worth recalling a few simple ideas concerning line profiles that helps in understanding. The main factors influencing line profiles in SN spectra can be listed as follws:

- velocity of envelope expansion - $v \propto R(radius)$
- abundance of material
- distribution of ion with R, inside or outside envelope - thin shells, thick shells, isotropic distribution, clumping
- opacity as a function of R
- asymmetries and viewing angle
- optical depth of lines

In what follows we will give some examples to demonstrate these various effects.

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2. Photospheric Absorption

In the early photospheric phases of SN1987A near maximum light absorption lines of BaII were observed and the identification of the BaII6142 line virtually unblended put the identifications and enhancement beyond doubt. Lines of other s-process elements such as SrII were also identified. One can see immediately from visual inspection that the BaII6142 line is narrower than other absorption lines suggested that the line is formed over a narrower range of velocity and therefore since $v \propto R$, the absorption is restricted to a smaller radius than other absorptions. It has been shown (Mazzali & Chugai 1995) that there is an overabundance of Ba by a factor of $\sim$ 2.5, this factor corresponding to that by which the LMC is underabundant relative to the Sun. Other Type IIP SNe such as SN1990H do not show an overabundance of BaII where solar abundances give a good match to its observed spectrum. It is still a puzzle how the enhancement occurred and how it was confined presumably in the progenitor star of SN1987A, and why the Ba abundance perhaps coincidentally is then near the solar value.

3. Emission Lines

The following very brief description helps one to understand some shapes of emission lines.

Assuming a spherically symmetric model envelope:

- Emission confined to a thin spherically symmetric shell gives a rectangular profile, with FWHM = 2 × radial expansion velocity.
- Emissivity uniform throughout the sphere gives a parabolic profile with FWHM = $\sqrt{2}v(max)$.
- No emissivity inside a central region with velocity $v < v(1)$ results in a flat-topped profile for $\Delta\lambda < v(1)\lambda(0)/c$.

These conditions apply for optically thin or optically thick cases. The presence of dust adds some extra effects on profiles.

3.1. Clumping and Asymmetries in Core-Collapse SNe

For obvious reasons SN1987A has been the best studied SN from outburst resulting in many of the effects reported below. Nevertheless other SNe have shown some of the profile effects reported for SN1987A. During the period 115-673 days past outburst the emission part of the PCygni profile of Hα was not smooth but showed evidence of 5 clumps (Hanuschik et al. 1993). These had been preceded earlier by an emission component of Hα now known as "the Bochum event". The 5 clumps remained constant in velocity with time. Until dust formed near day 530, giving rise to a blue shift of the line emission discussed later, there was an excess of flux on the red (or far) side in the interval 0-1000 km/sec resulting from the asymmetric clumping. They are clumps and not holes because holes could not produce the observed increase of flux at the time of onset. Since emergence of X rays occurred at the same time it is reasonable to assume that X rays and heating of clumps occurred in the inner regions where Comptonization of γ-rays occurred after some outward mixing. The model required to explain the observed profile after dust formation requires the clumps embedded in the dusty zone whose radius is 0.6 R (R being the outer radius of the envelope). This model might be refined by taking into account the fact that the dust may have formed both uniformly and in optically thick clumps.

Near IR spectra near day 500 (Spyromilio et al. 1990) show that lines of [FeII], [NiI], and HeI have a redshifted excess (asymmetry) while the hydrogen line Paβ does not. At day 377 [FeII] shows the red excess while MgI] does not. Thus Fe group elements have a spatial distribution predominating on the far side and possibly causing the extra heating in the Hα clumps as a result of radioactive decay of ^{56}Co.

The profiles of the IR lines of [FeII] at 18 and 26 μ around 408 days (Haas et al. 1990) are consistent with the [FeII] 1.26 μ profile alluded to above. They clearly demonstrate that Fe has been mixed into the H zone because the [FeII] profiles extend to > 3000 km/sec when the minimum velocity for H is 2100-2400 km/sec. The reported modelling of the [FeII] line profiles shows that Fe could extend to 15000 km/sec (a result that depends on defining accurately the location of the faint wings) with a possible hole at the centre (dependent on interpreting the observed profiles as flat-topped).

SN1999em another Type IIP SN also showed evidence of asymmetry (Elmhamdi et al. 2003). This was revealed by Hα profiles at day 97 when theoretical profiles for a spherically symmetric envelope were subtracted from the observed one. This subtraction left residuals at velocities of -4000 and +2000 km/sec. The residual at -4000 km/sec might be explained by the non-monotonic behaviour of τ but over-excitation remains on the far side. This apparent over-excitation on the far side is supported by an examination of the profiles of Hα and HeI 1.083 μ near day 150. Both show an asymmetry with the red side predominating. The fact that the HeI line is narrower may be a result of the fact that the non-thermal excitation of HeI does not extend out to the full hydrogen-rich envelope radius.

It is a cause for concern perhaps that so far the asymmetry or over-excitation always has occurred on the far side of the envelopes.

3.2. Nebular Spectra of the Type Ia SN1991bg

The nebular spectrum of a Type Ia SN such as SN1991bg, an intrinsically faint object offers the possibility of modelling and discriminating amongst various emission lines that make up the spectrum because of the low expansion velocity. It has been shown (Mazzali et al. 1997) that many, if not most, of the prominent features in the optical region can be interpreted to be due to lines of [FeII], [FeIII], and [CoIII]. However the best model fits still leave residual flux remaining to be accounted for. The observed profile of the [CoIII]5890,5908 line which is not flat-topped shows that in this case there is not a hole in the distribution of Co. A comparison of profiles of a sample of Type Ia SNe at similar phases shows a wide range of FWHM. These widths correlate with intrinsic luminosity at maximum and also with the mass of ^{56}Co produced of which there is an order of magnitude range in Type Ia SNe.

4. Dust in Core-Collapse SNe

The blue shift of the peaks of optical emission lines at day 530 after the outburst of SN1987A gave a clear signal that dust had formed in the envelope. It was accompanied by an increase in the IR emission as this dust was heated by the conversion of γ-rays into non-thermal and thermal electrons whose energy was subsequently converted into non-thermal radiation heating the dust. One can test various configurations of the dust in the envelope by computing line profiles. Dust confined to thin shells at any radius in the envelope produces flat-topped profiles and a blue shift unlike that observed. On the other hand dust distributed uniformly through the envelope or at least in the metal-rich region where the main diagnostic lines are formed produces profiles similar to the observed ones (Lucy et al. 1989). In principle a red extended wing might give evidence of a finite albedo of the dust grains which in its turn could diagnose the size of dust particles. In the case of SN1987A the albedo was very small or negligible. The wavelength dependence of the effect of dust suggested that there was an amorphous component of the dust with particle sizes comparable to the wavelength of light. A study of the profile of [OI]6300,6363 in SN1999em revealed a somewhat different situation for the formation of dust (Elmhamdi et al. 2003). A blue shift occurred at a slightly earlier phase than in SN1987A, but moreover the flat-topped profiles could only be reproduced invoking an extremely high dust opacity ($\tau = 50$) with a much more constricted confinement of the dust to the central regions.

5. Interaction with Circumstellar Matter

The Type IIn SN1995G was observed (Pastorello et al. 2002) who showed that at early and even late phases the spectra was distinguished by line of FeII having PCygni profiles. (Chugai & Danziger 2003) showed that profiles actually consist of two components in both emission and absorption. The narrow component is associated with a dense wind while the broad component is associated with a thin shell at the supernova envelope boundary. A model of the light curve and the measured expansion velocity led to a mass of material $\sim 1M_{\odot}$ released about 8 years before the explosion result in an energy release that could have been detected. Unfortunately an archive search shows no relevant observations at that time.

Another example of ejecta-wind interaction is that of SN1988Z observed by (Turatto et al. 1993) and modelled by (Chugai & Danziger 1994). Three different components comprise the profile of $H\alpha$. The broad component is emitted by the envelope, the intermediate component at the interface of the envelope with dense wind clumps or a dense equatorial wind, and the narrower component from the undisturbed circumstellar material. This is a case where more extensive and better s/n profiles might distinguish between the two models for the intermediate component.

6. Gamma-ray Line Profiles

The radioactive β-decay of ^{56}Co and ^{57}Co produces more than 10 γ-ray lines many of which were detected from SN1987A with space vehicles (Leising et al. 1990) & (Kurfess et al. 1992). The 847 keV line, the strongest from ^{56}Co, was observed (Tueller et al. 1990) with sufficient resolution and s/n at day 613 to show that while a Gaussian fit was reasonable the profile was shifted to lower energies and was broader than would be expected with a spherically symmetric model in which some mixing was allowed. Since the profile shape required small optical depths but the fluxes required large optical depths the only obvious way to resolve these contradictions was to invoke asymmetry and/or clumping. This seems to be at least qualitatively in agreement with what was deduced from the optical and IR spectra.

7. Conclusions

It is at some level pleasing to note that one can arrive at similar conclusions by using line profiles in different energy ranges - optical, IR, and γ-rays. Nevertheless there are some major problems remaining to be solved, some of which will require careful and detailed follow-up of future SNe. Others will require still better physical understanding and modelling of currently available data.

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