ANALYSIS OF THE SPECTRUM OF THE TYPE V SUPERNOVA SN1986J

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Abstract: The supernova SN1986j resembles the prototypical Type V supernova SN1961v in the relatively slow ~1000 km/s expansion velocity, the slow light curve, and also in the Hα dominated spectrum. The optical spectrum is similar to the spectra of some novae, and some OB stars with massive winds, being characteristic of a nebular plasma at about 10^{10} cm^{-3} and 10^4 K. What makes SN1986j exceptional is its tremendous radio luminosity, the brightest radio supernova observed to date. The radio emission indicates the presence of a massive circumstellar wind, with which the SN ejecta are now colliding. Since the cooling time of the optically emitting gas is about an hour, a heat source is required to power the light curve. Shocks moving back into the ejecta offer a natural heat source, and account quantitatively for the observed luminosity and spectral character of SN1986j. The large Hα/Hβ ratio is attributed to trapping of Lyα, which pumps the $n = 2$ level of hydrogen, causing a finite optical depth in Balmer lines, and converting Hβ to Pα and Hα. The ratio of the derived H($n = 2$) density and column density yields a size for the Hα emitting region consistent with the thickness of a cooling shock, but less than 10^{-7} of the 10^{17} cm VLBI size. An important discriminant between shock models and photoionization models of the spectrum is that shocks predict Lyman 2-photon emission. The mass of the optically emitting material in SN1986j is about 1 $M_\odot$, substantially less than the 2000 $M_\odot$ argued in the case of SN1961v by Utrobin. However, there may be, and probably is, considerably more unobserved ejecta. This material should reveal itself as the remnant of SN1986j continues to evolve.

Introduction: SN1986j was discovered at the VLA (Rupen *et al.* 1987) as a radio source in the edge-on spiral galaxy NGC 891. The distance to NGC 891 is $\approx 7.6 h^{-1}$Mpc, making SN1986j the most luminous radio supernova to date. Prior epoch radio observations at the VLA and Westerbork show that SN1986j was present as a 6 cm radio source at ~1/3 the present luminosity in 1984, before which only upper limits are available. Thus SN1986j is at least 2 years old. The radio spectral index indicates that the source is optically thick at 20 cm. The VLBI FWHM radius of the object is about 7×10^{16} cm at 7.6 Mpc. Rupen *et al.* reported an optical spectrum, taken in September 1986, which reveals SN1986j as a low ionization emission line object, showing emission lines of H I, He I, O I and Fe II, with FWHM line widths of ~1000 km/s. The Balmer decrement is unusually large, Hα/H$\beta \approx 60$. The visual magnitude was ≈ 19.5 in September 1986, about 1 magnitude fainter than a prior epoch observation taken in January 1984. Between 1977 and 1984 upper limits exist at ~18th magnitude. Based on the similarities between this object and the Type V supernova SN1961v (Zwicky 1965), including an unusually low expansion velocity, a slow (years near maximum) light curve, a large Hα/Hβ ratio,

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and prominent He I recombination lines, Rupen *et al.* classified the supernova as Type V.

Plasma Diagnostics: An optical spectrum of SN1986j is reported by Rupen *et al.* (1987). We obtained a second spectrum in October 1986; the new spectrum is similar to the old, but covers a slightly wider range 4000-9800 Å.

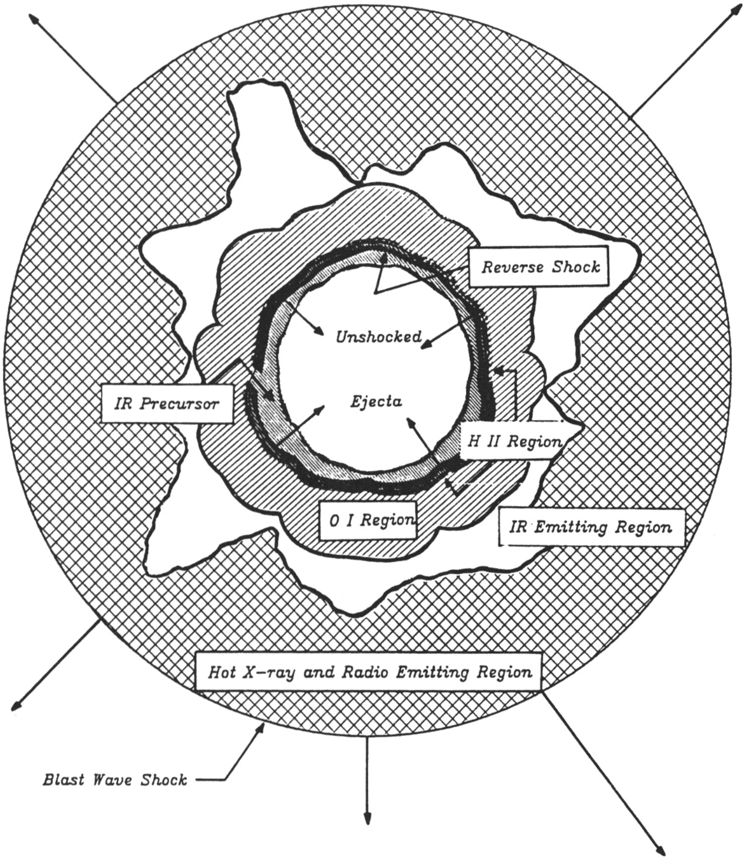
The weakness of Paschen lines (H 3-10,11,12) indicates that the large $H\alpha/H\beta$ ratio is most likely not due entirely to interstellar absorption; from the Paschen to Balmer line ratios we derive an extinction $A_V \approx 2$ in agreement with Rupen *et al.*

If it is assumed that hydrogen is collisionally ionized, and that the ionization of oxygen is tied to hydrogen by charge exchange, then the observed ratio [OII] λ7320/[O I] λ6300 ≈ 2 implies a temperature $\approx$ 13,000 K. The temperature is lower if hydrogen is photoionized, but this paper does not pursue that possibility. Since the O I temperature is probably lower than the O II temperature (see below), 13,000 K is probably a lower limit on the temperature of the region where O II and Hα emit. If the O/H abundance is at least cosmic, then the large ratio Hα/[O II] λ7320 $\approx$ 50 requires either a low temperature or a high density to suppress the [O II] emission; for a temperature $\gtrsim$ 13,000 K, the required electron density is $n_e \gtrsim 3\times10^9\,\mathrm{cm}^{-3}$. On the other hand, the weakness of the OI λ7774 recombination line relative to [O II] λ7320 implies an upper limit of $n_e \lesssim 3\times10^{10}\,\mathrm{cm}^{-3}$. We conclude that the density and temperature of the optically emitting region are $n_e \approx 10^{10}\,\mathrm{cm}^{-3}$ and $T \approx 10^4$ K. The high density is consistent with the presence (absence) of (un)observed forbidden lines in the spectrum.

There are a number of indications that the plasma is inhomogeneous, and that the optically emitting region may be only a fraction of the total. The O I temperature deduced from [O I] λ5577/[O I] λ6300 is only $T \approx$ 5,000 K for any electron density higher than $10^8\,\mathrm{cm}^{-3}$. At the same time, the presence of He I recombination lines requires temperatures $T \gtrsim$ 20,000 K (while the absence of [O III] λ4363 constrains $T \lesssim$ 20,000 K). The optical spectrum shows no evidence of any continuum; this implies an electron scattering optical depth less than unity, which in turn implies a mean electron density $\bar{n}_e \lesssim 2\times10^7\,\mathrm{cm}^{-3}$ over a VLBI radius of 7×10^{16} cm. The inference is that the bulk of the plasma may be relatively cool, neutral, and unobserved.

What Powers the Light Curve?: At $n_e \approx 10^{10}\,\mathrm{cm}^{-3}$ and $T \approx 10^4$ K, the cooling time of the emitting plasma is about the recombination time which is about 1 hour. Consequently, a heat source is required to power the light curve. Possible heat sources include:
(1) Photons still diffusing out of the SN fireball? No - there is no evidence of any optical continuum.
(2) Radioactivity? No - none left at ~3 years old; also, the supernova should have been brighter in the past.
(3) Photoionization? This possibility appears difficult to rule out; it requires a hot (nonthermal?), nonextended source with a luminosity $\approx 10^7 L_\odot$, such as, perhaps, a Very Massive Object, or a mini-quasar. Chevalier (1987) has proposed a central pulsar to power the optical display.
(4) Shocks? As we now argue, shocks are expected, and account quantitatively for the observed luminosity and spectral character of SN1986j.

Shocks: The picture we are proposing of SN 1986j is illustrated schematically in the Figure below.



The luminous radio emission implies the presence of a massive circumstellar wind, with which the supernova ejecta are presumably colliding (Chevalier 1982). A free-free optical depth greater than unity at 20 cm implies an electron density in the wind of $n_e(\mathrm{wind}) \gtrsim 5\times10^4\,\mathrm{cm}^{-3}$ at a radius of $r = 7\times10^{16}\,\mathrm{cm}$, for a wind density profile going as r^{-2}. The collision of ejecta with such a wind will drive shocks into the ejecta at ~10 km/s if the expansion velocity of the ejecta is a few 1000 km/s and the ejecta density ~$10^{10}\,\mathrm{cm}^{-3}$. Note that the inferred mass of the wind is $\gtrsim 0.3\,M_\odot$ outside 7×10^{16} cm; the original wind mass would be a factor $7\times10^{16}\,\mathrm{cm}/R_{\mathrm{star}}$ greater.

The expected Hα luminosity, which is about 1 photon per H atom entering the shock, $4\pi r_{\mathrm{shock}}^2 n_{\mathrm{H}} v_{\mathrm{shock}}$ photons per unit time, equals the observed Hα luminosity if the shock radius is $r_{\mathrm{shock}} \approx 5\times10^{16}$ cm, close to that observed.

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At an electron density $n_e \approx 10^{10}\text{cm}^{-3}$, and given the observed size and expansion velocity of SN1986j, Lyα is trapped, escaping mainly by 2-photon emission, provided that no alternative escape route is available, for example absorption by dust grains. If Lyα escapes mainly by 2-photon emission, then the density of excited $n=2$ hydrogen is $n_{\text{H}(n=2)} \approx 10^6\text{cm}^{-3}$ for an electron density of $n_e \approx 10^{10}\text{cm}^{-3}$. The excited hydrogen density is lower if other escape routes exist. The high density of excited hydrogen suggests the possibility that Balmer lines may have an appreciable optical depth; this would then account for both the large Hα/H$\beta \approx 60$ ratio, since Hβ is converted into Pα and Hα, and also for the strength of OIλ8446, which is pumped by Lyβ converted from Hα. Note that consistency between the optical depths of Hα and Hβ implies that the O/H abundance is near cosmic. The required Balmer optical depths imply a column density in excited hydrogen of $N_{\text{H}(n=2)} \approx 10^{14}\text{cm}^{-2}$, whence a total H II column density of $N_{\text{HII}} \approx 10^{18}\text{cm}^{-2}$, much smaller than the total hydrogen column density of perhaps 10^{26}cm^{-2} through the ejecta, but roughly consistent with the cooling column density in a shock.

In a shock, [O I] is emitted in a cooler quasi-neutral region downstream of the Hα and [O II] emitting region, consistent with the lower temperature deduced from the spectrum. The [O I] emitting zone is ~5000 (ratio of cooling column densities) times thicker than the Hα zone. The observed [O I] luminosity implies an O I mass $\approx 3\times10^{-4}\text{M}_\odot$, corresponding to a total mass in the O I zone of $\approx 1\text{M}_\odot$ for cosmic O/H. The mass of the Hα emitting zone is 1/5000 of this.

One curious feature of the optical spectrum of SN1986j is the presence of several lines, notably O Iλ8227, arising from recombination of O II in an excited ground state configuration. The only viable mechanism for exciting these lines appears to be charge exchange between H($n=2$) and excited O II.

Conclusions: We argue that the emission line spectrum of SN1986j is powered by a reverse shock moving at ~10 km/s into SN ejecta at a density of $\sim 10^{10}\text{cm}^{-3}$. The shock is driven by the collision of the ejecta with a massive circumstellar wind. The wind itself is being shocked at ~1000 km/s, producing the observed bright nonthermal radio emission.

The large observed Hα/Hβ ratio is attributed to Lyα trapping, which pumps the $n=2$ level of hydrogen, causing a finite optical depth in Balmer lines, and converting Hβ to Pα and Hα.

An important prediction of the shock model of the spectrum is of Lyman 2-photon continuum. Photoionization models predict no such continuum.

The inferred mass of the optically emitting regions is only $\sim 1\text{M}_\odot$, well short of the $\sim 2000\text{M}_\odot$ deduced by Utrobin (1984) for the prototypical Type V supernova SN1961v. However, it is likely that the emitting material in SN1986j represents only a small fraction of the total.

Oxygen and nitrogen abundances appear cosmic.

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