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SPECTROSCOPIC EVIDENCE FOR INHOMOGENEITIES IN THE EJECTA OF THE TYPE Ib SUPERNOVA 1985F

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ABSTRACT

A moderate-resolution spectrum of the Type Ib supernova 1985F in NGC 4618, obtained 8.5 months past maximum brightness, reveals small-scale irregularities (FWHM $\approx$ 100–250 km s^{-1}; relative amplitude $\approx$ 2%–10%) in the profile of the broad blend of [O I] λ6300 and [O I] λ6364. These same features are also visible 4 months later, but they are $\sim$40% narrower and $\sim$20% stronger than in the first spectrum. Small-scale fluctuations have previously been seen in the [O I] profiles of SN 1987A at a comparable time past maximum. One likely interpretation is that high-density clumps ($\delta\rho/\rho \gtrsim 0.1$) surrounded by regions of lower density are beginning to form in the ejecta. If such inhomogeneities continue to grow, as suggested by the SN 1985F data, then the 0.5 ms pulsar in SN 1987A may have been detected at a time when our line of sight intersected an unusually continuous series of "holes" between the clumps. It is also shown that the profile of Mg I] λ4571 is significantly different from that of [O I] λ6300, implying that the mixing within the ejecta is incomplete.

Subject headings: galaxies: individual (NGC 4618) — line profiles — stars: individual (SN 1985F) — stars: supernovae

I. INTRODUCTION

One of the most interesting aspects of the Type II SN 1987A is that we will be able to observe, at reasonably close range, the transition of an exploding star into an expanding supernova remnant. Based on the very filamentary visual appearance of the Crab nebula, we expect that the ejecta of SN 1987A will eventually form clumps and filaments of gas. Such clumps would not easily be visible during the first few months after maximum brightness because the ejecta are optically thick, and the spectrum consists of broad P Cygni profiles superposed on a thermal continuum. When the expanding gases become optically thin to a particular transition, on the other hand, it should be possible to detect irregularities in the corresponding emission line. Preliminary evidence for clumping only 1 yr after core collapse can be seen in the high-dispersion spectrum of the [O I] $\lambda\lambda$6300, 6364 lines illustrated by Stathakis and Cannon (1988). Small-scale irregularities, having a full width at half-maximum intensity (FWHM) of 50–200 km s^{-1}, are visible at the same relative velocities in each of the two independent profiles.

The possibility of clump formation in the ejecta takes on additional significance in view of the recent optical detection (Kristian *et al.* 1989) of a pulsar in SN 1987A. This object was found surprisingly early, at a time when the ejecta should have been optically thick to visible radiation, but all further attempts to confirm its presence have failed. The early detection, and the subsequent nondetection, can be understood if ejected gas is distributed in optically thick clumps that fill much of the volume and are separated by relatively transparent material. Although our line of sight should usually intersect one or more clumps, they may occasionally move out of the way, temporarily revealing the pulsar.

It is important to determine whether clump formation is a general property of supernovae, at least those in which core collapse is the explosion mechanism. Here we argue that SN 1985F, a Type Ib object believed to have resulted from a Wolf-Rayet progenitor star (Begelman and Sarazin 1986; Filippenko and Sargent 1986), showed small-scale structure in its late-time [O I] profiles similar to that in SN 1987A.

II. PROFILE IRREGULARITIES IN SN 1985F

On 1985 February 28 we discovered a peculiar supernova, 1985F, near the nucleus of the late-type spiral galaxy NGC 4618 (Filippenko and Sargent 1985, 1986). Originally this object was thought to be unique, but it was later reclassified as a SN Ib (Gaskell *et al.* 1986), based on a comparison of its optical spectrum with a late-time spectrum of the SN Ib 1983N. Indeed, the light curve compiled by Tsvetkov (1986) showed that SN 1985F was already about 8.5 months past maximum brightness at the time of our discovery.

A high-quality CCD spectrum (resolution $\approx$ 2.6 Å) of the exceptionally strong [O I] $\lambda\lambda$6300, 6364 lines in SN 1985F is illustrated in Figure 4 of Filippenko and Sargent (1985). There it can be seen that several narrow peaks, at approximately the same relative velocities, are present in both components. Other, smaller, irregularities are also visible in the blue wing of [O I] λ6300, although severe blending makes it difficult to distinguish the same features in the [O I] λ6364 profile.

To verify that the small-scale fluctuations are intrinsic to the supernova ejecta, we can measure their relative velocities in the two independent [O I] profiles, both of which originate from the same upper level of the neutral oxygen atom. Figure 1*a* shows an expanded plot of the [O I] blend in SN 1985F. The redshift of NGC 4618 (cz = 549 km s^{-1}), determined from

[1] Guest Observer, Palomar Observatory, which is owned and operated by the California Institute of Technology.
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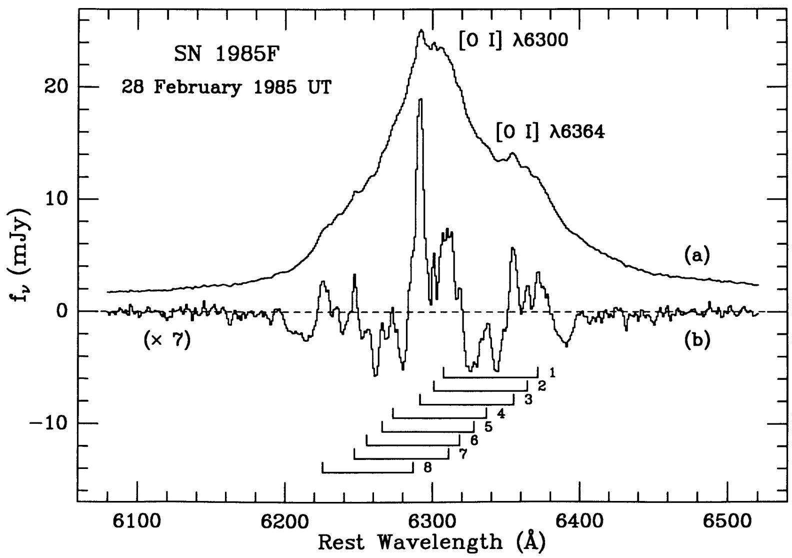

FIG. 1.—(*a*) Spectrum (1 Å bin^{-1}) of the [O I] blend in SN 1985F. Note the "triplet" of irregularities near the centroid of each of the two [O I] lines. (*b*) The [O I] "residual spectrum," produced by subtraction of a smoothed version of spectrum (*a*) and arbitrarily scaled by a factor of 7. Pairs of [O I] λλ6300, 6364 "peaks" having the same relative velocity are indicated (see Table 1).

narrow emission lines produced by the H II region on which SN 1985F is superposed, has been removed. To isolate the many apparent fluctuations in the profile, a procedure similar to "unsharp masking" (e.g., Schweizer and Ford 1985) was used. The spectrum was first smoothed with a rectangular boxcar having a width of 30 Å, and the smoothed version was subsequently subtracted from the original data. The residuals, scaled by a factor of 7 for clarity, are plotted in Figure 1*b*. Considerable structure is evident. Most of it must be real; the signal-to-noise (S/N) ratio per pixel is very high everywhere except in the line wings.

Casual inspection of Figure 1*b* reveals a basic pattern of "peaks" and "dips" which appears twice.[3] Specifically, the prominent "triplet" of peaks centered on 6300 Å is also seen around 6364 Å, and the "doublet" of dips flanking 6270 Å is mirrored by the one centered on 6334 Å. Table 1 lists the measured wavelengths (in the rest frame of NGC 4618) of peak pairs identified in the bottom portion of Figure 1. Despite the presence of blends, at least eight pairs with components having virtually the same redshift relative to the rest wavelengths of the [O I] lines (λλ6300.32, 6363.81) are visible. Obvious pairs of dips are also present, but are not marked to avoid confusion.

The largest [O I] λ6300 peak (at 6273.0 Å) is roughly 3 times stronger than the corresponding [O I] λ6364 peak (at 6336.5 Å), in agreement with the ratio of transition probabilities of these two lines. Although most of the other marked pairs do not appear with the expected 3/1 intensity ratio, they are still believed to be physically associated [O I] lines; the ratios are altered by blends with additional lines and by the fact that the smoothing process affects different regions of the asymmetric overall profile by different amounts. An excellent example of a partially blended pair is number 7 in Figure 1: the blue component (at 6247.0 Å) is quite isolated, whereas the red component (at 6311 Å) is obviously blended with the [O I] λ6300 line (at 6307.5 Å) of pair 1.

[3] Here we will refer to "peaks" as local maxima in Fig. 1*b*, even if they do not exceed zero flux. Similarly, a "dip" is defined to be a local minimum and need not actually have negative flux.

Some of the identified pairs in Figure 1 and Table 1 probably do not represent physical associations, of course, because the overlap of many lines can lead to wavelength coincidences. In particular, a few of the features can be interpreted in two different ways—either blueshifted or redshifted with respect to the rest frame of NGC 4618. For instance, part of the blended red component in pair 4 might actually be the *blue* component corresponding to the red peak at ~6400 Å. Most of the pairs were found by initially identifying a peak in the strong blue wing of [O I] λ6300, and then finding its counterpart in the blue wing of [O I] λ6364; thus, a majority of the pairs in Table 1 have a relative blueshift, not a redshift. Note, however, the dip at ~6390 Å, which is probably [O I] λ6364 redshifted by 1234 km s^{-1}; the corresponding [O I] λ6300 dip is at 6326 Å, partially blended with the [O I] λ6364 dip of another pair. To some extent, the apparent predominance of blueshifted pairs might also be a consequence of obscuration.

The FWHM of a reasonably unblended peak or dip in the residual spectrum (Fig. 1*b*), corrected for instrumental resolution, is 100–250 km s^{-1}—perhaps slightly larger than that of the small-scale irregularities in SN 1987A 1 yr past core

TABLE 1

PAIRS OF [O I] PEAKS, 1985 FEBRUARY 28 UT[a]

	[O I] λ6300.32		[O I] λ6363.81		
PAIR[b]	λ_{obs} (Å)	v (km s^{-1})[c]	λ_{obs} (Å)	v (km s^{-1})[c]	Δv (km s^{-1})[d]
1.........	6307.5:	342:	6371.5	362	−20:
2.........	6300.9	28	6364.3	23	5
3.........	6291.5	−420	6355.0	−415	−5
4.........	6273.0	−1300	6336.5	−1287	−13
5.........	6266.0	−1633	6328:	−1673:	40:
6.........	6255.5	−2133	6318.5	−2135	2
7.........	6247.0	−2537	6311:	−2488:	49:
8.........	6225.5	−3560	6287:	−3618:	58:

[a] Uncertain wavelengths (blends and weak peaks) indicated with a colon.
[b] Identification number of [O I] pair; see Fig. 1.
[c] Redshift (*cz*) of observed feature, in rest frame of NGC 4618.
[d] Difference in redshift between [O I] λ6300 and [O I] λ6364.

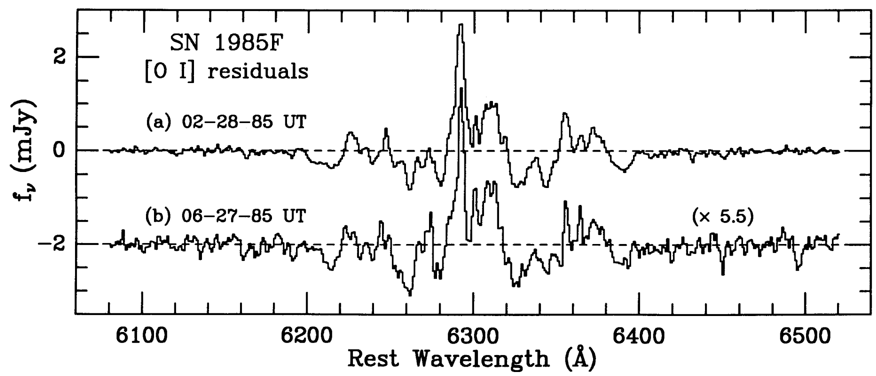

FIG. 2.—(*a*) Residual spectrum from Fig. 1*b*, shown on an absolute flux scale. (*b*) Residual spectrum 4 months later. The scale factor of 5.5 corresponds to the ratio of integrated [O I] fluxes in the February and June spectra. The features are narrower, and their relative amplitude is greater, than in (*a*). An absorption dip at ~6498 Å is produced by underlying starlight.

collapse. This corresponds to about 3%–7% of the FWHM (~3400 km s^{-1}) of the strong, broad [O I] emission lines in SN 1985F. The amplitude of the various peaks and dips relative to the smoothed profile is roughly 2%–10%, comparable to their fractional velocity width. No obvious correlation between position in the line profile and relative amplitude of profile irregularities is visible in Figure 1*b*.

Of great interest is the temporal behavior of the irregularities in the [O I] profiles. Unfortunately, most of our data do not have sufficiently high S/N ratio or resolution to permit a worthwhile comparison, though a good spectrum was obtained with the Hale reflector on 1985 June 27 UT. A scale factor of 5.5 was applied to this spectrum, making its [O I] flux similar to that on February 28. As before, residuals were determined by subtracting a smoothed spectrum from the original data. The two residual spectra are displayed in Figure 2. It is clear that the same basic pattern of peaks and dips is present in both cases, once again confirming that the irregularities are not due to noise. Several significant differences are also evident: in June the features are roughly 40% narrower, and ~20% stronger, than in February.

III. PROFILE DIFFERENCES IN SN 1985F

Small-scale irregularities in SN 1985F might also appear in spectral lines other than [O I]. To test for this, Figure 3 shows the [O I] blend and the somewhat noisier Mg I] λ4571 line on the same velocity scale. Although the Mg I] profile exhibits a few real fluctuations, they are less numerous than in [O I], and they are not at the same relative velocities.

Another, more striking, aspect of Figure 3 is the obvious difference in the overall profiles of Mg I] and [O I]. The Mg I] profile was scaled by a factor of 8.3 before plotting, so that its blue wing closely matches that of [O I] λ6300, but its peak is much narrower. When the Mg I] line is subtracted from the [O I] blend, the residual is double peaked, as shown in Figure 3*c*. If Mg I] and [O I] had the same shape, the profile of the remaining [O I] λ6364 would resemble that of Mg I].

One can also see that the centroid of Mg I] λ4571 (defined near the peak) is offset from zero velocity by several hundred km s^{-1}, whereas that of [O I] λ6300 is not. This suggests that part of the line actually represents [Mg I] λ4562, but this transition is very weak in the models of Fransson and Chevalier (1989). Alternatively, some of the distant gas emitting redshifted Mg I] λ4571 may be obscured if the optical depth to electron scattering is several tenths. Dust forming in the ejecta could also cause this effect. In any case, even if the line centroid is shifted to zero velocity, subtraction of the Mg I] line from the [O I] blend leaves a [O I] λ6364 profile that differs substantially from that of Mg I]. (As noted by Fransson and Chevalier 1989, however, the lines appear too similar to have been produced by gas in completely unmixed layers.)

IV. DISCUSSION AND CONCLUSIONS

The small-scale irregularities described in § II demonstrate that there must have been inhomogeneities in the ejecta of SN 1985F as early as 8.5 months after maximum brightness (or ~9 months after the explosion). There are two obvious possibilities for their nature. One is that they represent radial "fingers" of material having a higher speed than their immediate surroundings. Such fingers might arise from Rayleigh-Taylor instabilities in the expanding ejecta, and they have been

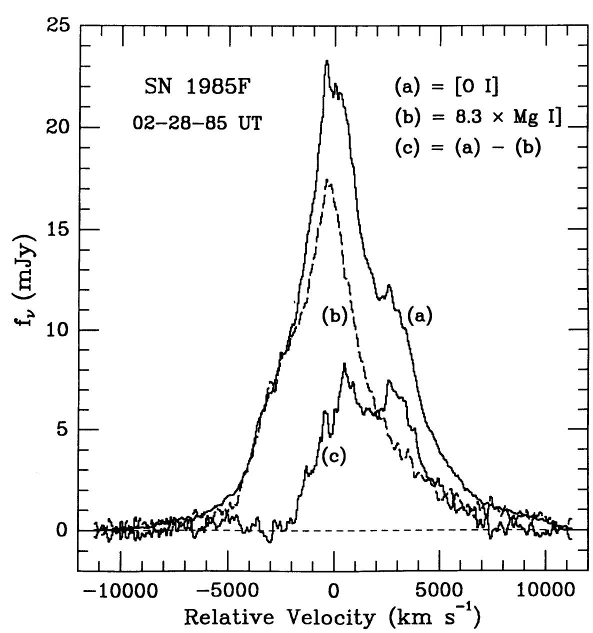

FIG. 3.—(*a*) Spectrum (50 km s^{-1} bin^{-1}) of the [O I] λλ6300, 6364 blend in SN 1985F. The very weak, extreme line wings (|*v*| ≳ 11,000 km s^{-1}) are ignored. (*b*) Spectrum of the Mg I] λ4571 line, scaled by a factor of 8.3 and shifted so that the wavelength 4571 Å appears at zero velocity. (*c*) The difference between spectra (*a*) and (*b*), showing that Mg I] and [O I] do not have the same profile.

postulated in the case of Ni^{56} to explain the early appearance of γ-rays and soft X-rays from SN 1987A (e.g., Arnett *et al.* 1989).

Another idea is that the inhomogeneities are local density enhancements that give rise to more emission at certain velocities in the overall line profile. Since the density (ρ) of the [O I]-emitting material is near, or somewhat above, the critical density of 1.4×10^6 cm^{-3}, to first order the [O I] emissivity (per unit volume) is proportional to the density. Thus, the observed 2%–10% variations in the intensity of [O I] emission close to the centroid of the broad line correspond to $\delta\rho/\rho \gtrsim 0.02$–0.1. We emphasize that the density inhomogeneities could actually be much larger; many layers of gas ejected with a range of velocities (e.g., $v \propto r$) contribute flux near the core of the line, effectively smoothing the profile. If the clumps represent 100% density contrast, and there are 100 clumps (each coherent over 100 km s^{-1}) through a typical diameter spanning 10,000 km s^{-1}, intensity fluctuations of 10% are easily explained.

High-density clumps may form as a result of hydrodynamic instabilities in the ejecta. Naively, one would expect their relative amplitude to increase with time, and their velocity width to decrease, just as observed. The evolution of the inhomogeneities should be studied in more detail, both observationally and theoretically. If holes having sufficiently low density (and low optical depth) can form, then it might be possible to occasionally view the very center of the supernova, as Kristian *et al.* (1989) seem to have done when they discovered the 0.5 ms pulsar in SN 1987A. Clumping may also be necessary to reconcile the observed light curve of SN 1985F with that expected from the core collapse of a Wolf-Rayet star (Ensman and Woosley 1988).

A somewhat different interpretation of the fluctuations in the [O I] profile is that they are caused by spherical shells of oxygen having a range of densities. This is supported by the mild degree of symmetry among the peaks or dips (e.g., pairs 1 and 3) in Figure 1*b*. Despite the likely possibility that most of the symmetry is coincidental, it would be worthwhile to determine the density structure with Fransson's (1987) method.

One final result of this study is that Mg I] λ4571 and [O I] λ6300 in SN 1985F did not have exactly the same profile 9 months after the explosion; hence, the ejecta were not thoroughly mixed. This is of interest because Fransson and Chevalier (1989) invoked substantial mixing in their model of SN 1985F to eliminate flat-topped theoretical line profiles, and to obtain reasonably similar Mg I] and [O I] shapes. Moreover, much evidence for mixing in the SN 1987A ejecta has been found (see Arnett *et al.* 1989). Further studies of many line profiles should clarify the extent to which mixing has occurred.

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Note added in proof.—Large [O I] optical depths in the high-density clumps of gas may be partly responsible for the low (< 3/1) intensity ratio of [O I] λ6300 to [O I] λ6364 in some of the pairs identified in Figure 1*b*. The overall intensity of the *broad* [O I] lines, however, appears to be ~3/1.

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