Helium Emission in the Type Ic SN 1999cq

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ABSTRACT

We present the first unambiguous detection of helium emission lines in spectra of Type Ic supernovae (SNe Ic). The presence of He I lines, with full width at half maximum \( \approx 2000 \text{ km s}^{-1} \), and the distinct absence of any other intermediate-width emission (e.g., H\( \alpha \)), implies that the ejecta of SN Ic 1999cq are interacting with dense circumstellar material composed of almost pure helium. This strengthens the argument that the progenitors of SNe Ic are core-collapse events in stars that have lost both their hydrogen and helium envelopes, either through a dense wind or mass-transfer to a companion. In this way, SN 1999cq is similar to supernovae such as SN 1987K and SN 1993J that helped firmly establish a physical connection between Type Ib and Type II supernovae. The light curve of SN 1999cq is very fast, with an extremely rapid rise followed by a quick decline. SN 1999cq is also found to exhibit a high level of emission at blue wavelengths (\( \lesssim 5500 \text{ \AA} \)), likely resulting from either an unusually large amount of iron and iron-group element emission or uncharacteristically low reddening compared with other SNe Ic.

Subject headings: binaries: close—stars: evolution—stars: mass-loss—supernovae: general—supernovae: individual (SN 1999cq)

1. Introduction

The nature of supernovae (SNe) of Type Ib and Ic has been the subject of much speculation; see Harkness & Wheeler (1990) for an early review, and Clocchiatti et al. (1997) for a more recent discussion. Spectra of SNe Ib/c lack the hydrogen lines that distinguish SNe II, yet they are also missing the deep absorption near 6150 \( \text{\AA} \) (thought to be blueshifted Si II \( \lambda 6355 \)) that characterizes SNe Ia. The defining characteristic of SNe Ib is the presence of strong He I lines near maximum light. This is followed by a nebular-phase spectrum dominated by emission lines of [O I], [Ca II], and Ca II. SNe Ic are spectroscopically quite similar to SNe Ib, but they do not show the strong He I lines. This results in the occasional designation of SNe Ic as “helium-poor” SNe Ib (Wheeler et al. 1987).
The most widely accepted model for the SN Ib/c explosion mechanism is that it is related to the mechanism of SNe II—core collapse in massive stars—but that SNe Ib/c have lost their hydrogen (and helium, in the case of SNe Ic) envelopes through winds or mass transfer to a companion (e.g., Woosley, Langer, & Weaver 1993; Yamaoka, Shigeyama, & Nomoto 1993; Nomoto et al. 1994; Iwamoto et al. 1994). There is considerable circumstantial evidence that the progenitors of SNe Ib and Ic are massive stars. SNe Ib/c are associated with Population I stars (Wheeler & Levreault 1985; Uomoto & Kirshner 1985; Harkness et al. 1987; Huang 1987; Van Dyk 1992; Bartunov et al. 1994, Van Dyk, Hamuy, & Filippenko 1996), their hosts are virtually always late-type galaxies (Porter & Filippenko 1987), and they exhibit radio emission (e.g., Weiler et al. 1998, and references therein), thought to be the result of interaction with circumstellar material (Chevalier 1982, 1984). Contrasted with this are the favored progenitors of SNe Ia, white dwarfs (e.g., Branch et al. 1995; Livio 1999), although models for SNe Ib/c using white dwarfs as progenitors have been proposed (e.g., Branch & Nomoto 1986; Iben et al. 1987). The late-time spectra of SNe Ib/c are also very similar to those of SNe II, with the obvious exception of the hydrogen lines. Perhaps the best evidence connecting SNe Ib/c with SNe II is the direct transformation of an individual supernova from one type to another. SN 1987K was initially spectroscopically a Type II, but the late-time spectra resembled those of SNe Ib (Filippenko 1988); it thus earned a new label, Type IIb (after Woosley et al. 1987). Unfortunately, the actual transition was not observed. Filippenko (1992) and Jeffery et al. (1991) also suggested that the Type Ic SN 1987M showed evidence of hydrogen in its spectrum.

Like SN 1987K, SN 1993J was spectroscopically a SN II in the first few weeks after explosion, but then began to exhibit the He I lines of a SN Ib, making it a SN IIb (Filippenko & Matheson 1993; Filippenko, Matheson, & Ho 1993; Swartz et al. 1993a; Wheeler & Filippenko 1996). The various theoretical models rapidly converged on the same general concept—a massive star that had lost most, but not all, of its hydrogen envelope (Woosley et al. 1994; Wheeler & Filippenko 1996, and references therein). Gradually the [O I], [Ca II], and Ca II emission lines emerged, making the spectrum of SN 1993J closely resemble that of an aging SN Ib, although the hydrogen emission never fully disappeared. Indeed, the hydrogen emission became very prominent at late times, but this was almost certainly the result of circumstellar interaction (Filippenko, Matheson, & Barth 1994). Qiu et al. (1999) document thoroughly a similar transition in SN 1996cb.

Although there has been no object showing as definitive a transformation between SNe Ib and Ic as SN 1993J or SN 1996cb showed between SNe II and Ib, there have been several SNe Ic with possible signs of helium in their spectra. These include the detection of He I λ10830 in SN 1990W (Wheeler et al. 1994; based on this line, they propose SN 1990W was misclassified, and should be Type Ib), SN 1994I (Filippenko et al. 1995), and SN 1994ai (Benetti, quoted in Clocchiatti et al. 1997), in addition to the discovery of other He I lines at high velocity in a reanalysis of SN 1994I, SN 1987M, and SN 1988L (Clocchiatti et al. 1996b) and in SN 1997X (Munari et al. 1998). (See, however, Baron et al. [1999] and Millard et al. [1999] for cautionary arguments.) By analogy to the models of SN 1993J, one could postulate that the progenitors of SNe Ic have not only had
their hydrogen envelope removed, but most or all of their helium layer as well (Harkness et al. 1987; Yamaoka, Shigeyama, & Nomoto 1993; Swartz et al. 1993b; Iwamoto et al. 1994; Nomoto et al. 1994), so the weakness or absence of He I lines is the result of small abundance. The SNe Ic that exhibited some helium would then be the analogs of SN 1993J, but with the transition less obvious. An alternative explanation for the cause of the differences between SNe Ib and Ic relies on the need for a large amount of non-thermal excitation to form He I lines (Harkness et al. 1987; Lucy 1991). The source of this excitation is electrons accelerated by the γ-rays emitted by the decay of radioactive $^{56}$Ni synthesized in the explosion. In this scenario, helium could be present in SNe Ic, but the $^{56}$Ni is not mixed into the helium layers, and so cannot produce the helium lines (e.g., Wheeler et al. 1987; Shigeyama et al. 1990; Hachisu et al. 1991). Whatever the cause of the helium features, the characteristics of the previous detections of helium in SNe Ic (absorption at high velocity) suggest that the helium is in the ejecta, not the circumstellar material.

The spectrum of a truly transitional object between SNe Ib and Ic could provide clues as to whether the difference between them is the result of abundances, mixing, or both. In this paper we present optical to near-infrared (near-IR) spectra of SN 1999cq, a SN Ic with unusual intermediate-width helium emission lines, along with an unfiltered light curve. We propose that the helium lines represent the detection of material lost from the progenitor shortly prior to explosion. We also find an excess of blue emission in comparison with other SNe Ic, with implications for iron and iron-group element abundance, mixing, and the reddening of SN 1999cq.

2. Observations

SN 1999cq was discovered by the Lick Observatory Supernova Search (LOSS) (Modjaz & Li 1999) on 1999 June 25.4 UT, (JD 2,451,354.9; note that all calendar dates used are UT) at an unfiltered magnitude of $\sim$ 16.0. It was present on previous images at similar magnitudes (June 22.4, $\sim$ 15.9; June 19.4, $\sim$ 15.8). An image taken on 1999 June 15.4 showed nothing at the position of the SN to a limit of $\sim$ 19.0 mag. The supernova was 1.5′ east and 4.1′ south of the nucleus of UGC 11268. A spectrum obtained July 9.4 (JD 2,451,368.9, hereinafter “the July spectrum”) indicated that SN 1999cq was of Type Ib or Ic, and starting to enter the nebular phase, although Na I D did show a P-Cygni profile (Filippenko 1999).

This spectrum was obtained with the Kast double spectrograph (Miller & Stone 1993) at the Cassegrain focus of the Shane 3-m reflector at Lick Observatory with an exposure time of 1800 s. Reticon 400 × 1200 pixel CCDs were used in both cameras. The slit was oriented at a position angle of 160° to include the galaxy nucleus. The optimal parallactic angle (Filippenko 1982) was 81°, but the low airmass (1.1) and the large slit width (3′) imply that the differential light losses were negligible. Standard CCD processing and optimal spectral extraction were accomplished
with IRAF\(^1\). We used our own routines to flux calibrate the data, using the sdO comparison star BD +28°4211 (Stone 1977) in the range 3300–5400 Å and the sdG comparison star BD +17°4708 (Oke & Gunn 1983) in the range 5300–9900 Å. Telluric absorption bands were removed through division by the intrinsically featureless spectrum of BD+17°4708 (Wade & Horne 1988). The dispersion of the spectrum is \(\sim 5\) Å per pixel. We obtained a second spectrum on 1999 August 17.3 (JD 2,451,407.8, hereinafter “the August spectrum”) under almost identical conditions. The only differences were a narrower slit width (2″), a slightly higher airmass (1.2), and the use of BD +26°2606 (Oke & Gunn 1983) as the comparison star for the red wavelengths.

As SN 1999cq lies in a complex region only 4.′′4 from the nucleus of UGC 11268, background sky subtraction and the extraction of the supernova were extremely difficult. There is H II region contamination over a considerable portion of the long slit (\(\sim 48′′\) out of the \(\sim 125′′\) spatial extent of our exposures). The least contamination of the object was achieved by choosing sky regions for background subtraction very near the supernova. There is still some galaxy contamination, made more complicated by unusually strong emission lines. In fact, the regions of the supernova spectrum near Hα+[N II] \(\lambda\lambda 6548, 6583\) and [S II] \(\lambda\lambda 6716, 6731\) still show some unavoidable residual subtraction errors. Incomplete removal of the very strong Na I D night-sky emission line also affects the spectrum.

The unusual nature of SN 1999cq was not immediately recognized, so it was not followed photometrically through standard \(UBVRI\) filters. However, UGC 11268 is part of the LOSS sample of galaxies and is thus imaged regularly (every three to four days) with the 0.76-m Katzman Automatic Imaging Telescope at Lick Observatory (KAIT; Treffers et al. 1997; Richmond, Treffers, & Filippenko 1993). The detector used by KAIT is a SITe 512 × 512 pixel CCD with a field of view of 6.′8 × 6.′8. The observations are taken without a filter, so the light curve for SN 1999cq (Figure 1) is measured in unfiltered magnitudes. Photometric calibration of KAIT images indicates that the unfiltered response is similar to a standard \(R\) filter. The images were reduced using a galaxy subtraction technique; SN 1999cq is in a very complex region of the host galaxy, and traditional aperture or point-spread-function (PSF) fitting photometry would not perform well. The template image of UGC 11268 was taken 1998 September 16 with a limiting magnitude of \(\sim 20\). The template is shifted spatially, scaled to the same intensity level and PSF, and then subtracted from each individual observation. Photometry is then performed on the galaxy-subtracted images using PSF fitting in DAOPHOT with more than 10 stars in the field used to construct the PSF. The magnitude of SN 1999cq was calculated by averaging its magnitude relative to all the stars used to determine the PSF. For all of the observations of SN 1999cq the limiting unfiltered magnitude was \(\sim 19\).

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\(^1\)IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
3. Results

Our spectra of SN 1999cq are shown in Figure 2. A low value for the Galactic component of reddening \(E(B-V) \approx 0.05\) mag is found using the Galactic maps of Schlegel, Finkbeiner, & Davis (1998). There is no obvious absorption near the location of Na I D at the redshift of the host galaxy \((\sim 7900\) km \(s^{-1}\), determined from the nuclear H\(\alpha\) emission line; Marzke, Huchra, & Geller [1996] found \(7890 \pm 20\) km \(s^{-1}\) for UGC 11268). To determine a 1\(\sigma\) upper limit on the equivalent width (EW) of this line, we used the relation \(EW(1\sigma) = \Delta \lambda \times \Delta I\), where \(\Delta \lambda\) is the width of a resolution element (\(\AA\)) and \(\Delta I\) is the 1\(\sigma\) root-mean-square (rms) fluctuation of the spectrum around a normalized continuum level, based on the derivation of Hobbs (1984). The value we calculated for the Na I D line in the July spectrum of SN 1999cq is \(EW \lesssim 1.8\) \(\AA\). The Barbon et al. (1990) relation would then give \(E(B-V) \lesssim 0.45\) mag. For reasons discussed below, however, we feel that the intrinsic reddening is much lower than this upper limit. We note that the spectrum of the nucleus of UGC 11268 has a much higher signal-to-noise ratio than that of the supernova, and it shows a strong Na I D absorption line with an EW of \(\sim 1.7\) \(\AA\), for which the Barbon et al. (1990) relation gives \(E(B-V) \approx 0.44\) mag.

Figure 3 provides a montage of SNe Ib and Ic at similar phases of development for direct comparison with SN 1999cq. While the July spectrum of SN 1999cq in many ways resembles a typical SN Ic during the transition to the nebular phase (e.g., emission lines of [O I] \(\lambda\lambda\ 6300, 6364\), [Ca II] \(\lambda\lambda\ 7291, 7324\), O I \(\lambda 7774\), and the Ca II near-IR triplet), there are two striking differences. The first is the presence in SN 1999cq of several He I lines in emission at an intermediate velocity width compared with the other lines. (Note that SN 1991ar may show similar emission, but it is much less compelling.) The second is the unusually large amount of emission at blue wavelengths in SN 1999cq.

Most of the emission features in the July spectrum have a full width at half-maximum (FWHM) of 7000-9000 km \(s^{-1}\). There are three narrow, but resolved (FWHM \(\approx 2000\) km \(s^{-1}\)), lines that we identify as He I \(\lambda 5876, 6678,\) and \(\lambda 7065\). (A typical unresolved night-sky emission line has FWHM \(\approx 750\) km \(s^{-1}\)). The velocity width and flux are uncertain for the He I \(\lambda 6678\) line because of poor subtraction of nearby [S II] \(\lambda\lambda\ 6716, 6731\) emission (from H II regions) and also that its redshifted position of \(6860\) \(\AA\) is coincident with the telluric B-band. In addition, He I \(\lambda 5876\) is superposed on the P-Cygni emission of Na I D. These issues, along with the noisy nature of the spectrum, make flux determinations problematic. If we assign a flux value of 1.00 to He I \(\lambda 5876\), then He I \(\lambda 6678\) is 0.65 and He I \(\lambda 7065\) is 1.61, with large uncertainties given these caveats.

The August spectrum (Figure 2b) was extremely weak; the supernova had faded considerably and was very difficult to detect. (This was more than 40 days past the last KAIT image where SN 1999cq was visible, i.e. brighter than the limiting unfiltered magnitude of \(\sim 19\).) Despite this, we still recover clear signs of the supernova. The Ca II near-IR triplet is present, as is the strong amount of emission at blue wavelengths that characterizes the July spectrum. Most importantly, one of the helium lines (He I \(\lambda 7065\)) is still clearly visible with approximately the same velocity
The photometric evolution of SN 1999cq is fairly unusual. It is difficult to make direct comparisons with other SNe as our values for SN 1999cq are unfiltered magnitudes. It rose rapidly, climbing above the limiting value of 19 mag by 3.2 mag in 4 days. The comparison with the $R$-band rise of SN Ic 1994I (Richmond et al. 1996) in Figure 1 is particularly dramatic. SN 1999cq then dropped quickly as well, falling 0.2 mag in the 6 days after the first detection, and then 3.0 mag in the remaining 16 days that it was above the detection limit. During a similar period (25 days) following maximum in the $R$ band, SN 1994I fell 2.3 mag (Richmond et al. 1996), while SN 1993J declined by 1.0 mag (Richmond et al. 1994). If there are photometric sub-classes for core-collapse SNe (Clocchiatti et al. 1996a, 1997), then SN 1999cq clearly belongs to the “fast” class. Models for SN 1994I have been able to reproduce a rapidly declining light curve with a core-collapse event in stars whose envelopes have been lost to a companion (Iwamoto et al. 1994; Woosley et al. 1995).

There have been no distance measurements for UGC 11268, although it is a good candidate for IR Tully-Fisher distance determination (Haynes et al. 1999). If the recession velocity ($7900 \text{ km s}^{-1}$) is chiefly due the Hubble flow then the distance of UGC 11268 is 118 Mpc (using $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$), which is a distance modulus of 35.4 mag. Although our photometric points are unfiltered magnitudes, and the zero-point of our scale is not well determined, our brightest observed magnitude of 15.8 and this distance modulus give us a rough estimate of the absolute magnitude of SN 1999cq near maximum of $-19.6$ mag. While this value is quite uncertain, it is still intriguing. An absolute magnitude this bright would make SN 1999cq one of the most luminous SNe Ic ever observed. Clocchiatti et al. (1999) report an absolute $V$ magnitude of $-19.2 \pm 0.02$ or $-20.2 \pm 0.02$ for the Type Ic SN 1992ar. (The two values are the results of extrapolation of the light curve using two different assumptions for its shape—the fainter value if it followed the slow-type light curve, the brighter one if it were a fast-type decliner.) In addition, the Type Ic SN 1998bw (possibly associated with gamma-ray burst 980425) had an absolute magnitude of $M_V = -19.35 \pm 0.05$ (Galama et al. 1998), with an extremely rapid rise to maximum (Woosley, Eastman, & Schmidt 1999). As Clocchiatti et al. (1999) discuss in detail, the existence of SNe Ic as bright as SNe Ia complicates the identification of high-redshift SNe used to study cosmological parameters (Riess et al. 1998; Perlmutter et al. 1999). Without spectra of SN 1999cq near maximum light, it is not possible to determine whether or not it could be mistaken for a SN Ia under the difficult conditions presented by the observations of cosmologically distant SNe. Nevertheless, such luminous SNe Ic emphasize the need for careful spectroscopic study of the high-redshift SNe.

4. Discussion

4.1. Helium Lines

The detection of the intermediate-width helium lines in the spectra of SN 1999cq requires the presence of helium in the circumstellar environment of the progenitor, but not in the ejecta of the
exploding star. The width of the lines implies that the helium-emitting region is interacting with the expanding ejecta. The conspicuous absence of Balmer emission suggests a very low abundance of hydrogen. An obvious solution is that SN 1999cq is interacting with material from the progenitor lost through a wind or mass transfer to a companion.

It is also possible that the source of the helium lines is material not originally from the SN progenitor, but rather a companion sufficiently nearby to be affected by the explosion. As mentioned before, mass transfer facilitated by a companion is a common model for SNe Ib/c progenitors, and thus the presence of such a companion must be considered. We note that Chugai (1986) and Marietta, Burrows, & Fryxell (1999) predicted a similar velocity width ($\lesssim 1000$ km s$^{-1}$) for the lines of hydrogen from the interaction of a SN Ia with its companion, although those calculations were for material entrained in the ejecta and the resulting emission would not be visible until several hundred days after the explosion. For SN 1999cq, however, such a companion star would probably be hydrogen-rich if it had accreted hydrogen from the progenitor; thus, it is more likely that the helium lines are evidence of helium-rich material that was lost from the progenitor itself prior to core collapse.

The helium lines exhibit unusual line intensity ratios. In a typical hydrogen-rich atmosphere with a temperature of $(1 - 2) \times 10^4$ K and electron density $n_e \approx 10^2 - 10^8$ cm$^{-3}$ one would expect the ratio of He I $\lambda 7065$ to He I $\lambda 5876$ to be $\sim 0.1 - 0.2$ (Osterbrock 1989). The ratio observed here (1.61) implies a very different state, most likely related to the non-local-thermodynamic-equilibrium excitation required for the helium emission (Lucy 1991). The work of Almog & Netzer (1989), however, studying the emission-line spectrum of He I over a wide range of physical conditions, indicates that the large 7065/5876 ratio could be the result of a very high density. We cannot directly apply the numbers calculated by Almog & Netzer, as their models were for helium in a hydrogen atmosphere. Nonetheless, their results indicate that for a small range of densities ($n_e \approx 10^{10}$ cm$^{-3}$, at $T = 10^4$ K), the strength of the 7065 line becomes greater than that of 5876. Such a large ratio of 7065/5876 has been observed in other SNe that exhibited circumstellar interaction through helium and hydrogen emission lines, including intermediate-width lines (e.g., SN 1996L; Benetti et al. 1999). Assuming that the trend of increasing 7065/5876 with increasing density applies to an effectively pure helium atmosphere, then the intermediate-width helium lines in SN 1999cq originate in an extremely dense environment.

Hydrogen and helium emission lines of similar width were also present in the spectra of SN 1988Z (Filippenko 1991; Stathakis & Sadler 1991; Turatto et al. 1993). Chugai & Danziger (1994) (hereinafter CD94) interpreted this intermediate-width component of the emission as evidence for slow radiative shocks propagating either in dense clumps of wind material or in a dense equatorial belt, with both embedded in a uniform wind. Unfortunately, without multiple epochs and well defined broad lines, it is not possible to apply the details of CD94’s models. Moreover, SN 1999cq has the added complication of an apparently pure helium wind, where the issues of excitation and radiative transfer are not as well known; such a calculation is beyond the scope of this paper. Therefore, we cannot differentiate between the two scenarios of CD94. Nonetheless, the qualitative
arguments still apply. Intermediate-width components in the spectra of SNe are likely to be the result of ejecta interacting with dense material lost from the progenitor prior to explosion. The lack of narrow (unresolved) and broad (FWHM $\gtrsim 5000$ km s$^{-1}$) He I lines in our spectra of SN 1999cq implies that the uniform component of both of CD94’s models is either extremely tenuous and/or that helium excitation is more difficult in such rarefied environments.

As noted above, several models for the progenitors of SNe Ib and Ic postulate that they are massive stars that lose their envelopes prior to core collapse. Both SN 1987K and SN 1993J provided direct evidence for this mechanism by exhibiting hydrogen emission from the low-mass layer of the progenitor’s original envelope that remained. Because the late-time spectra of SNe Ib and Ic are similar (see, e.g., Filippenko 1997), the analogous transformation of a SN Ib to a SN Ic would be much more subtle. In fact, SNe that have broad He absorption lines that fade during the transition to the nebular stage are, by definition, still called SNe Ib. SN 1999cq thus provides evidence for a link in another way. The He I lines we observe indicate an almost pure helium mass loss—exactly what the above models have assumed to produce the stripped-envelope progenitors of SNe Ic.

One question about SN 1999cq remains: Is it legitimately a SN Ic? The late-time spectra of SNe Ib and Ic are similar overall, but the velocity-widths of the lines are different. Schlegel & Kirshner (1989) found the widths of [O I] $\lambda\lambda$6300, 6364 and [Ca II] $\lambda\lambda$7291, 7324 in late-time spectra of SNe Ib to be FWHM = 4500 $\pm$ 600 km s$^{-1}$. In contrast, Filippenko et al. (1995) reported FWHM values for [Ca II] of 9200 km s$^{-1}$ for SN Ic 1994I and 6200 km s$^{-1}$ for SN Ic 1987M, for spectra at similar phases ($\sim$ 4.6 months after maximum). For [O I], the FWHM was 7700 km s$^{-1}$ for SN 1994I and 7500 km s$^{-1}$ for SN 1987M. In SN 1999cq, the FWHM of the [O I] line is 7800 km s$^{-1}$, while the [Ca II] line is 8000 km s$^{-1}$ (given the difficulty of determining a continuum level, the uncertainty of these values is $\sim$ 15%). The spectrum of SN 1999cq was obtained only a few weeks past maximum, but its rapid evolution (c.f. Figure 1) implies that the relative phase is at least comparable. Filippenko et al. (1995) interpreted the larger velocity-width of the lines in SN 1994I as indicative of either a higher explosion energy and/or a smaller ejected mass in comparison with SN 1987M. Following this interpretation, SN 1999cq would have an even larger explosion energy and/or smaller ejected mass. This is consistent both with the evidence for mass loss, as well as the large luminosity of the event, and it makes the classification of SN 1999cq as a Type Ic event more secure.

Another difference between SNe Ib and SNe Ic is the shape of their light curves. The light curves of SNe Ib decline more slowly, typically dropping only $\sim$ 1.5 mag. in the 25 days after maximum (B magnitude; Schlegel & Kirshner 1989). As noted before, in that same time SN 1994I dropped 2.3 mag. and SN 1999cq fell by 3.2 mag. This implies an even more rapid transition to the nebular phase than that of SN 1994I ($\lesssim$ 2 months; Filippenko et al. 1995). The first spectrum (July) was obtained only 24 days following the most recent image without the supernova (the temporal position relative to the light curve is marked in Figure 1), and it clearly shows the onset of nebular features. The rapid rise and fall of SN 1999cq also imply that it was of Type Ic.
There is no evidence in the spectra of SN 1999cq for the distinguishing characteristic of SNe Ib—broad helium lines, generally interpreted as P-Cygni profiles. We believe that the P-Cygni profile of Na I D is still evident in Figure 2. The relatively large amount of blue emission in SN 1999cq makes the P-Cygni absorption trough more difficult to discern, but it is there. The blue minimum of the line indicates an expansion velocity of 8300 km s$^{-1}$, well in agreement with the widths of the broad lines. If SN 1999cq did have broad He lines initially, they must have faded very quickly, while the Na I D line remained. Nonetheless, even if SN 1999cq were originally a SN Ib, the intermediate-width He I lines still imply pure helium mass loss.

4.2. Blue Emission

As Figure 3 shows, SN 1999cq also exhibits an anomalous “blue bump” of emission in contrast to other SNe Ic. This appears in both of our spectra (July and August). The spectra of the host galaxy nucleus and nearby H II regions extracted from the same long-slit exposures show no evidence for unusual blue emission. Given the extreme overlapping of lines, it is difficult to identify individual features other than perhaps Mg I $\lambda\lambda4571$ and some lines of Fe II.

One possible source for the blue emission is a mixture of overlapping iron lines. Clocchiatti et al. (1997) identified the Fe II lines at $\lambda\lambda4924$, $\lambda5018$, and $\lambda5169$ in the Type Ic SN 1983V. They also found Fe II blends of multiplets 27 and 28 ($\sim 4100 - 4400$ Å), multiplets 37 and 38 ($\sim 4500 - 4650$ Å), and multiplet 74 (near 6200 Å). Other possibilities include multiplets 3, 14, and 29 ($\sim 3800 - 4000$ Å), multiplets 43 and 50 ($\sim 4700 - 4750$ Å), multiplet 42 ($\sim 4900 - 5200$ Å), and multiplets 48 and 49 ($\sim 5200 - 5400$ Å) (e.g., Phillips 1976). There is clearly no dearth of potential iron lines in the region of our spectrum that shows this blue emission. In addition, there are several lines from other stable iron-group elements such as Co and Ni (see, e.g., Axelrod 1980).

The presence of such strong iron (and/or iron-group) lines in SN 1999cq compared to other SNe Ic might imply that the mixing of $^{56}$Ni was more extensive in SN 1999cq. This would, however, contradict the standard predictions of the mixing differences between SNe Ib and Ic (Baron 1992), but only if helium were still present in the atmosphere of the progenitor. If the progenitor of SN 1999cq had lost most or all of its helium, leaving a C-O core, then considerable mixing of $^{56}$Ni to the outer layers is possible, resulting in excess iron emission. This could still be consistent with models for mixing in SNe Ic as the $^{56}$Ni is not reaching beyond the C-O core into a helium layer. In addition, the bright absolute magnitude of SN 1999cq may imply the production of more $^{56}$Ni than is produced in a typical SN Ic, thereby providing the excess material to mix into the outer parts of the ejecta.

Given the relatively large cross-sections for the iron-group elements, however, the strong emission lines might not require overly large abundances. A fully quantitative spectral synthesis model would be necessary to determine the actual abundances. A further concern for the effect of mixing on the character of the spectrum is that macroscopic mixing of $^{56}$Ni could occur without necessar-
ily exciting helium, and thus produce the apparent excess of iron-group element emission without creating broad helium lines, as is observed in SN 1999cq. Therefore, SN 1999cq may not provide a discriminant between the mixing models for SNe Ib and Ic. While there are variations in abundances (mainly light elements) and light-curve shapes (which have implications for synthesized $^{56}\text{Ni}$) for SNe Ib and SNe Ic; e.g., Clocchiatti et al. 1997, and references therein), to our knowledge no other SN Ib or Ic has shown such extreme iron or iron-group emission. Spectra of other luminous SNe Ic (SN 1992ar, Clocchiatti et al. 1999; SN 1998bw, Branch 1999) do not show unusual emission at blue wavelengths.

Another explanation for the “blue bump” is related to the surrounding environment of the supernova. One way to increase the blue emission of an object is to scatter the spectrum off of interstellar dust, as in a light echo. This phenomenon has a long history of discussion in association with SNe (e.g., Zwicky 1940; van den Bergh 1975; Chevalier 1986; Schaefer 1987). It has only been definitively observed in two supernovae: SN 1987A (Suntzeff et al. 1988; Crotts 1988; Gouiffes et al. 1988) and SN 1991T (Schmidt et al. 1994; Sparks et al. 1999). With spectra from earlier epochs, one can match late-time echoes. Suntzeff et al. (1988) and Schmidt et al. (1994) each characterized the effects of scattering as a power law ($F_\lambda \propto \lambda^{-\alpha}$), with $\alpha$ values of $4.9 \pm 0.8$ and 2, respectively. (Crotts [1988] found $\alpha = 3.5 \pm 0.5$ from broad-band colors.) Not having other spectra of SN 1999cq, we instead compared it with spectra of the SNe Ic 1987M and 1994I that had been corrected by the scattering law. We find that $\alpha \approx 1.5$ gives a good fit. This variation of the exponent in the scattering power law is presumably related to the nature of the scattering dust. The scattering efficiency for particles of a size scale comparable to optical wavelengths decreases with decreasing size (although it will also decrease for particles much larger than optical wavelengths, eventually producing grey extinction), but the shape and composition of the particles has a significant enough effect on scattering to preclude much speculation regarding the nature of the dust (e.g., Yanamandra-Fisher & Hanner 1999).

As reddening is, in practice, the inverse process to scattering, a more likely solution related to environmental effects is a lack of extinction for SN 1999cq. Both SN 1994I and SN 1987M were considerably reddened. For SN 1994I, Ho & Filippenko (1995) found $E(B − V) = 1.0^{+1.0}_{−0.5}$ mag (assuming $R = A_V/E(B − V) = 3.0$) from high-resolution studies of the Na I D lines, but they considered $E(B − V) \lesssim 0.47$ mag a more likely limit; this is also the value Iwamoto et al. (1994) found from light-curve studies. Filippenko, Porter, & Sargent (1990) estimated the reddening of SN 1987M to be $E(B − V) \approx 0.44$ mag. The spectrum of SN 1995F in Figure 3 also shows a strong Na I D absorption feature (EW $\approx 1.0$ Å) that implies an $E(B − V)$ $\approx 0.25$ mag from the Barbon et al. (1990) relation. Dereddening these SNe using the extinction correction of Cardelli, Clayton, & Mathis (1989), with the O'Donnell (1994) modifications at blue wavelengths, results in spectra that effectively match the ones produced by correcting with the previously described scattering law (Figure 4).

As mentioned above, the intrinsic reddening of SN 1999cq is highly uncertain. The 1σ upper limit for $E(B − V)$ of 0.45 mag is reasonable when compared with other SNe Ic. A more quantitative
estimate, using techniques to be described elsewhere (Leonard et al., in preparation), is that the EW is consistent with zero, but with a $1\sigma$ uncertainty of 0.97 Å. Thus the reddening of $E(B-V) \lesssim 0.45$ mag is probably an overestimate, with $E(B-V) \lesssim 0.25$ being more likely. Given how well the dereddened spectra of other SNe Ic match SN 1999cq, it is plausible that it is not significantly reddened. We believe that what appears to be an anomalous level of blue emission might actually represent the true spectrum of an unreddened SN Ic, perhaps with unusually strong Fe II emission since SN 1999cq was such a luminous event. Without a reliable estimate of the extinction, though, this conclusion is highly uncertain.

5. Conclusions

Spectra of SN 1999cq reveal significant emission at blue wavelengths in excess of what is observed in other SNe Ic. Any interpretation of this emission is strongly dependent on the intrinsic reddening of SN 1999cq. If we assume SN 1999cq suffers little reddening, then its spectra are indicators of the relative significance of blue emission, presumably iron and iron-group lines, in SNe Ic. The blue emission would contribute almost equally with the standard red nebular lines ([O I], [Ca II], and Ca II), in contrast to typical SNe Ic. If SN 1999cq is as reddened as SNe Ic usually are, then the alternative solution for the excess blue emission of unusually strong iron and iron-group element emission would be just as interesting, with potential implications for the mixing of $^{56}$Ni into the outer parts of the progenitor and/or the total amount of $^{56}$Ni produced by the explosion. The detailed nature of the mixing of nickel must be understood to see if mixing models can actually produce the difference between SNe Ib and SNe Ic. If the helium is not present, mixing could still occur, but then the abundance of helium is the critical factor in determining whether or not the core collapse of a stripped star is observed as a SN Ib or a SN Ic.

We have also discovered He I emission lines with an intermediate velocity width in SN 1999cq, a SN Ic. Since such intermediate-width lines likely indicate the interaction of the SN ejecta with dense material lost from the progenitor star, we believe this provides evidence of an almost pure helium wind or mass transfer. If this is the case, then the mechanism that differentiates SNe Ib and Ic is similar to the mass loss or transfer that transforms a Type II core-collapse SN into a Type Ib/c. The He I lines in SN 1999cq have the signature of dense mass loss of a helium envelope, which would not be expected if differing degrees of mixing of $^{56}$Ni into the ejecta were the sole criterion for the difference between SNe Ib and Ic. SN 1999cq does not show a direct transformation such as that of SN 1987K, SN 1993J, or SN 1996cb, but, in the He I lines, we may be seeing a reflection of the last step in the process that creates the progenitors of SNe Ic.

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Fig. 1.— Light curve of SN 1999cq. Filled circles represent unfiltered magnitudes (approximately $R$ band) of the supernova; open circles represent the limiting magnitude for images in which the supernova was not visible. The error bars are estimates, not formal uncertainties for the magnitudes. Errors for the first four magnitudes of SN 1999cq are smaller than the size of the points. The crosses are the $R$-band light curve of SN 1994I (Richmond et al. 1996, Leuschner 0.5-m data only) scaled and shifted to match approximately the maximum value for SN 1999cq. The date of the July spectrum is also indicated.

Fig. 2.— Spectra of SN 1999cq from (a) 1999 July 9.4 and (b) August 17.3 with some line identifications. A recession velocity of $8200$ km s$^{-1}$, as determined from the centroid of the intermediate-width He I lines, has been removed. (The host galaxy nucleus has a recession velocity of $7900$ km s$^{-1}$.) Significantly poor subtraction of H$\alpha$ from nearby H II regions has been deleted from spectrum (b). Note the continuing presence of He I $\lambda 7065$, the Ca II near-IR triplet, and the excess blue emission in spectrum (b).

Fig. 3.— Spectra of various SNe (SN Ib 1991ar; SNe Ic 1987M, 1994I, and 1995F) at a similar phase of development as the July spectrum of SN 1999cq. (The SN 1991ar spectrum is 30 days past discovery [McNaught & Russell 1991] with no information relative to maximum; the SN 1987M spectrum is 96 days past $B$ maximum [Filippenko et al. 1990]; the SN 1994I spectrum is 56 days past $B$ maximum [Filippenko et al. 1995]; and the SN 1995F spectrum is 74 days past the earliest image [Vagnozzi, Piermarini, & Russo 1995] with no information relative to maximum). All have been deredshifted by the appropriate velocity and narrow emission lines have been removed, where applicable. The spectra show substantial similarity, the only major variation among them being the relative ratios of the features in the range $\sim 6100 - 6600$ Å. The broad lines in this region include [O I] $\lambda 6300$, and possibly Si II $\lambda 6355$ and C II $\lambda 6580$ (see, e.g., Baron et al. 1999; Millard et al. 1999). The dramatic differences that SN 1999cq exhibits are the intermediate-width He I lines and the considerable emission blueward of $5500$ Å. Note, however, that SN 1991ar may also have intermediate-width He I lines which had not been noticed previously. In addition, the O I $\lambda 7774$ line in SN 1999cq appears to be redshifted when compared with the other SNe. This is not evident in any other lines. We have no explanation for this anomaly, but we believe it does not affect our interpretation of the rest of the spectrum.

Fig. 4.— Spectrum of SN 1999cq (smoothed with a 3 pixel-width boxcar to emphasize the overall shape) compared with spectra of SN 1994I that have been (a) corrected for scattering, (b) corrected for reddening, and (c) uncorrected. The scattering correction was $F_\lambda \propto \lambda^{-1.5}$. Dereddening by $E(B-V) = 0.47$ mag was accomplished with the extinction corrections of Cardelli et al. (1989), including the O’Donnell (1994) modifications. Note that both the (a) and (b) versions of SN 1994I have distinctly different overall shapes when compared with (c). The increased level of blue emission evident in the corrected spectra of SN 1994I is a fairly good match to the amount of anomalous blue emission of SN 1999cq. The slope of the underlying continuum of SN 1999cq is clearly different from the observed spectrum (c) of SN 1994I.
Magnitude (unfiltered) vs. JD−2,451,300

SN 1999cq (●)
SN 1994I (×)

July spectrum taken
\[ f_\lambda \left( 10^{-15} \text{ ergs/s/cm}^2/\text{Å} \right) \]

**SN 1999cq (a)**

- Ca II
- Fe II
- He I/Na I D
- [O I]
- [Ca II]
- O I
- Mg I
- [Si II/C II (?)]
- Fe (?)

**Rest Wavelength (Å)**

(a) Spectroscopic data of SN 1999cq.

(b) Additional spectroscopic data, possibly showing different line features or different stage of the supernova.
