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THE EVOLUTION OF LATE-TIME OPTICAL EMISSION FROM SN 1979C

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ABSTRACT

Optical spectra of the bright Type II-L supernova SN 1979C obtained in April 2008 with the 6.5 m Multiple Mirror Telescope are compared with archival late-time spectra to follow the evolution of its optical emission over the age range of 11–29 years. We estimate an Hα flux decrease of around 35% from 1993 to 2008 but noticeable increases in the strength of blueshifted emission of forbidden oxygen lines. While the maximum expansion of the broad $\sim$ 6700 km s^{-1} Hα emission appears largely unchanged from 1993, we find a significant narrowing of the double-peaked emission profiles in the [O I] $\lambda\lambda$6300, 6364 and [O II] $\lambda\lambda$7319, 7330 lines. A comparison of late-time optical spectra of a few other Type II SNe which, like SN 1979C, exhibit bright late-time X-ray, optical, and radio emissions, suggests that blueshifted double-peaked oxygen emission profiles may be a common phenomenon. Finally, detection of a faint, broad emission bump centered around 5800 Å suggests the presence of WC-type Wolf–Rayet stars in the SN's host star cluster.

Key words: circumstellar matter – supernovae: general – supernovae: individual (SN 1979C) – supernova remnants

1. INTRODUCTION

SN 1979C was one of the brightest Type II supernovae (SNe) ever observed in the optical and radio. It was discovered in M100 on 1979 April 19 by G. Johnson (Mattei 1979; NGC 4321, $d = 15.2$ Mpc, Freedman et al. 2001), a galaxy which has had an unusually high number (five) of SNe (Panagia et al. 1980). SN 1979C's blue absolute magnitude was ≈ -20 mag, about 2–3 mag brighter than typical SNe of its kind in the optical, and it reached a 6 cm flux density of $\sim$ 8 mJy, implying a luminosity more than 200 times that of Cas A in the radio (Young & Branch 1989; Tammann & Schröder 1990; Gaskell 1992; Weiler et al. 1986, 1989).

Optical spectra near maximum light showed a featureless continuum that developed emission lines with expansion velocities $\gtrsim$ 8000 km s^{-1} typical of Type II SNe (Branch et al. 1981; Barbon et al. 1982). Dominating the spectrum after one month was strong and broad ($v \approx$ 9000–10,800 km s^{-1}) Hα emission with little or no P Cyg absorption. The relatively slow decline and evolution of the light curve classified the SN photometrically as a Type II-L (Panagia et al. 1980).

SN 1979C was optically recovered in 1990 over a decade after outburst (Fesen & Matonick 1993; hereafter FM93). Low-dispersion optical spectra showed broad but blueshifted, double-peaked and asymmetric emission lines of [O I] $\lambda\lambda$6300, 6364 and [O II] $\lambda\lambda$7319, 7330. Faint 6000 km s^{-1} broad Hα emission with an asymmetric profile stronger toward the blue was also seen. Follow-up ground-based optical spectra taken in 1993 with the Multiple Mirror Telescope (MMT) and near-UV spectra (2200–4500 Å) obtained in 1997 with the Faint Object Spectrograph (FOS) aboard the *Hubble Space Telescope* (*HST*) showed these same features as well as blueshifted, double-peaked emission lines of C II] $\lambda\lambda$2324, 2325, [O II] λ2470, Mg II $\lambda\lambda$2796, 2803, and [O III] λ4363 (Fesen et al. 1999; hereafter F99). The blueward peak was much stronger than the less blueshifted peak in the near-UV lines, which was interpreted as due to extinction within the expanding ejecta.

Radio flux density from SN 1979C has been extensively monitored over the last three decades, with observations beginning eight days after maximum optical light. These data show an initial decline in flux density followed by a flattening or possible brightening at an age of $\approx$ 10 yr (Weiler et al. 1991, 2001; Montes et al. 2000). The spectral index at late times has been relatively constant, although recent data suggest a probable flattening (Montes et al. 2000; Bartel & Bientenholz 2008). Potential quasi-periodic variations in its radio emission may be due to modulations of the progenitor star's circumstellar medium (CSM) by a binary companion (Weiler et al. 1992; Schwartz & Pringle 1996). Very long baseline interferometry (VLBI) observations suggest a near-free expansion and shell structure (Bartel & Bientenholz 2003, 2008).

Here we present a recent optical spectrum of SN 1979C and compare it against earlier spectra in order to follow the evolution of its late-time emission. Similarities between SN 1979C and a number of other Type II SNe observed at late times (> 5 yr) are also briefly discussed.

2. OBSERVATIONS

Encouraged by the success of exploratory spectra taken at MDM Observatory in 2007 December, low-dispersion optical spectra of SN 1979C were obtained with the 6.5 m MMT on Mount Hopkins, AZ, using the Blue Channel spectrograph on 2008 April 1. A 1″ wide slit and a 300 lines mm^{-1} 4800 Å blaze grating was used to obtain spectra spanning 3500–7500 Å with a resolution of $\sim$ 7 Å. A total of 4 $\times$ 1200 s exposures were taken at the parallactic angle under good but non-photometric seeing ($\approx$ 0″.7). Spectra were reduced and calibrated employing standard techniques in IRAF.[3] A strong blue continuum likely due to the star cluster in the vicinity of SN 1979C was removed in the final reduction.

[3] 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.

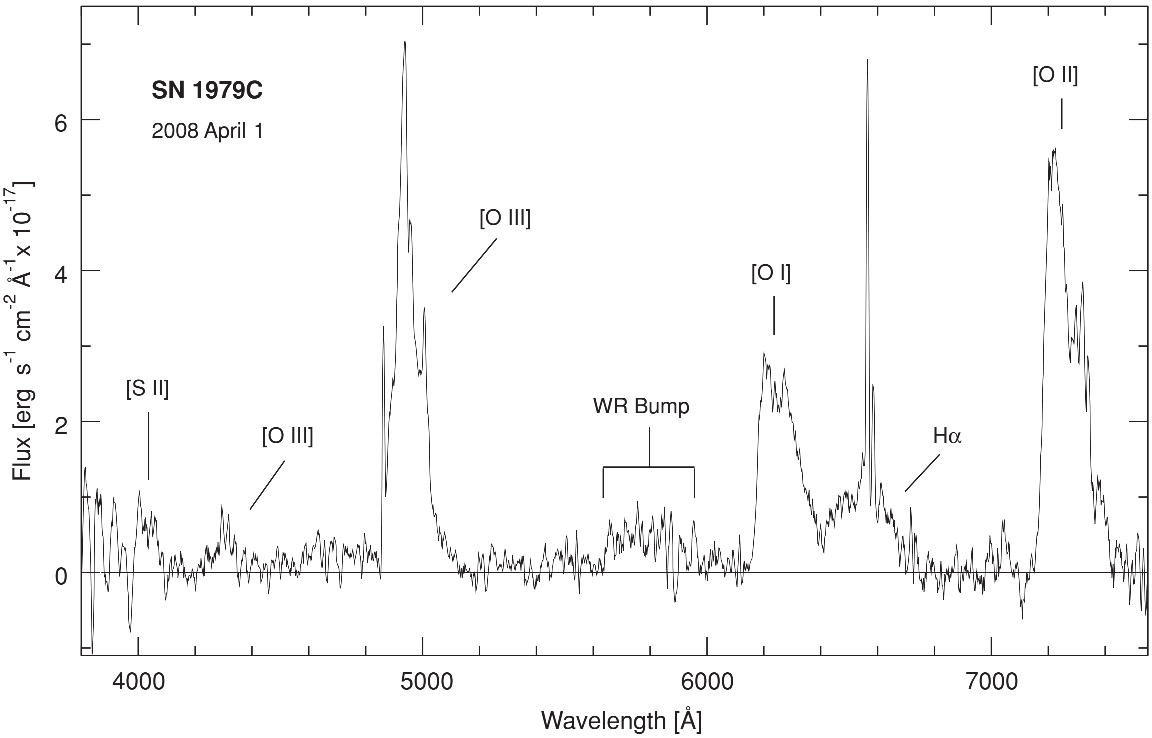

Figure 1. MMT spectrum of SN 1979C taken in 2008 April. A blue continuum has been removed from the observed spectrum.

3. RESULTS

Our 2008 spectrum of SN 1979C taken some 29 years after maximum light is shown in Figure 1 and plotted in the rest frame of M100 ($V = 1571$ km s^{-1}; Rand 1995). Broad Hα emission along with broad and multi-peaked lines of forbidden oxygen are visible in the spectrum. Narrow, unresolved lines are emission from an H II region local to the SN 1979C site. Below we discuss the main emission features observed. All listed wavelengths have been corrected to the rest frame of M100.

Hα. Faint, asymmetric Hα emission spanning approximately 6410–6710 Å (-7000 to +6700 km s^{-1}) is seen centered around the narrow H II nebular line at 6563 Å. Because the broad Hα emission merges toward the blue with [O I] $\lambda\lambda$6300, 6364 emission and toward the red with the [S II] $\lambda\lambda$6716, 6731 lines, the true maximum expansion velocities are uncertain. The MMT spectrum was taken on a mainly clear but not photometric night. Consequently, we have used a December 2007 MDM spectrum to estimate line fluxes. Our estimated flux for the broad Hα emission is $\sim 2 \times 10^{-15}$ ergs cm^{-2} s^{-1}, an $\sim$ 35% decrease from the $(3 \pm 0.5) \times 10^{-15}$ ergs cm^{-2} s^{-1} reported by F99.

[O I]. Like that seen in 1991 and 1993 (FM93, F99), the [O I] $\lambda\lambda$6300, 6364 line profile is strongly double-peaked (see Figure 1). We measure peaks at 6210 and 6275 Å, corresponding to expansion velocities of -4300 and -1200 km s^{-1} with respect to 6300 Å. The separation between the peaks in the 2008 spectrum is less than that seen in 1993 when they were at -4900 and -600 km s^{-1} (F99; see discussion in Section 4.1). On the other hand, the full expansion velocity of the [O I] line profile is -7000 to +1600 km s^{-1}, some 1000 km s^{-1} larger than that reported by F99. This difference might simply be attributable to the higher S/N and greater sensitivity of the more recent MMT observation.

[O II]. The [O II] $\lambda\lambda$7319, 7330 lines also show a broad, blueshifted double-peaked emission profile spanning a wavelength range of 7160–7420 Å. With respect to 7325 Å (the approximate weighted center of the two emission lines), this corresponds to an expansion velocity range of -6700 km s^{-1} to +3900 km s^{-1}. The profile shows two blueshifted emission peaks with one at 7220 Å (-4300 km s^{-1}) and a weaker peak near 7305 Å (-200 km s^{-1}). Similar double peaks were reported in F99 but at somewhat different velocities. Also, our new spectrum shows the less blueshifted peak is now weaker in strength compared to the more blueshifted peak. Although some emission from other lines such as [Ca II] $\lambda\lambda$7291, 7324 is possible, the similarities of the double-peaked profile across all oxygen lines suggests this emission is primarily from [O II].

[O III]. The strong emission observed around 4960 Å is blueshifted [O III] $\lambda\lambda$4959, 5007 line emission. The improved S/N of the 2008 MMT spectrum compared to earlier observations shows the [O III] profile clearly for the first time. With respect to the [O III] λ5007 line, a strong emission peak at 4935 Å corresponds to a velocity of -4300 km s^{-1}, which matches the blueshifted emission peak seen in the other oxygen lines. Measured to the red of 5007 Å, faint emission extends out to 5125 Å corresponding to a velocity of +7000 km s^{-1}. This velocity is significantly larger than +1600 km s^{-1} measured in F99, but, as noted earlier, the difference is likely attributable to the higher S/N and greater sensitivity of the 2008 observation. The narrow, unresolved line at 5007 Å is [O III] emission from the local M100 H II region, as is the narrow Hβ line at 4862 Å.

We identify faint emission near 4300 Å as blueshifted (-4300 km s^{-1}) [O III] λ4363 line emission. Assuming $E(B-V) = 0.34$ (F99), the observed dereddened I(4959+5007)/ I(4363) ratio is $\approx$ 17, implying electron densities of around 10^5 cm^{-3} assuming a temperature of 25,000 K. This ratio is much larger than the value of $\simeq$ 4 reported by F99, suggesting an appreciable decrease in density in the SN's O-rich ejecta over the last 15 years.

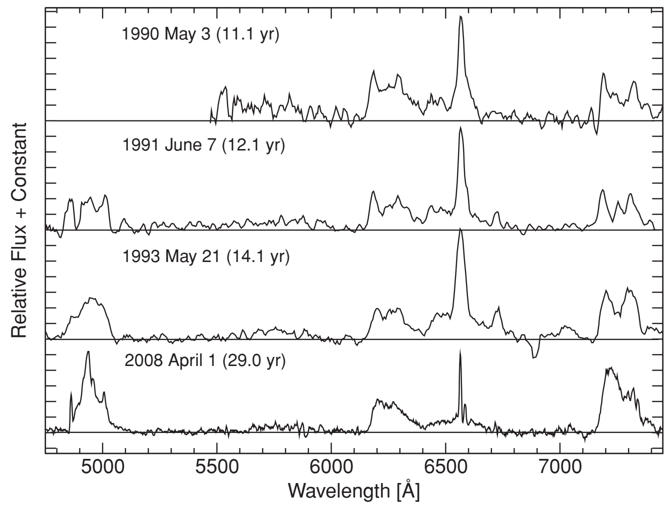

Figure 2. Optical spectra of SN 1979C spanning ages 11.1–29.0 yr. Approximate ages are with respect to an estimated optical maximum on 1979 April 15 (Panagia et al. 1980).

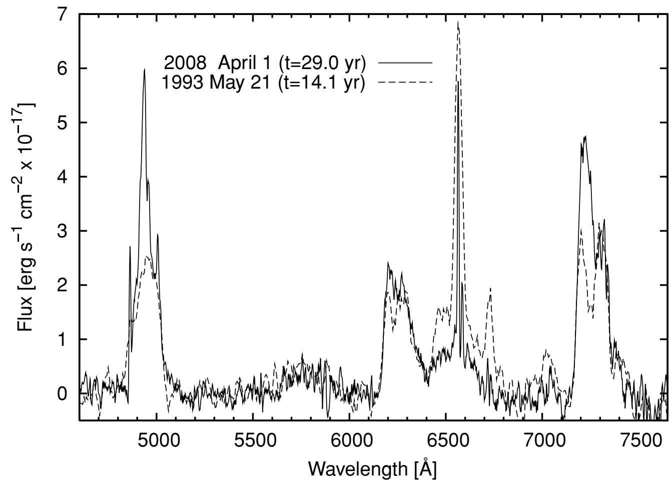

Figure 3. MMT optical spectra of SN 1979C at epochs $t = 14.1$ yr and 29.0 yr.

Broad emission at 5800 Å. Broad emission centered around 5800 Å and extending from 5670–5900 Å can be seen in Figure 1. Though faint, this emission is consistent with earlier reports of broad emission at 5700–5900 Å (FM93, F99). The position, broadness, and strength resembles the Wolf–Rayet (WR) emission "bump" due to C III λ5696, C IV λλ5801, 5812, and He I λ5876 observed in galaxies and clusters of stars having a population of evolved WR stars mainly of the WC type (Sidoli et al. 2006).

Other emission lines. Emission around 4050 Å is identified with blueshifted [S II] λλ4069, 4076, which is consistent with *HST* FOS spectra obtained in 1997 (F99). The lack of broad [S II] λλ6716, 6731 emission lines implies that electron densities for the S-rich ejecta lie above 10^4 cm^{-3}.

4. DISCUSSION

4.1. Evolution of Late-Time Optical Emission

Our spectrum shows that SN 1979C remains remarkably optically bright almost three decades after outburst. Its late-time X-ray, optical, and radio emissions are likely the result of interaction with a dense and extensive CSM environment left behind by the progenitor star (Chevalier & Fransson 1994; Weiler et al. 1986, 1989; FM93; Immler et al. 2005). In this scenario, the broad late-time Hα emission is due to shocked high-velocity H-rich ejecta, while broad oxygen lines are reverse shock heated O-rich ejecta.

Strong interactions between SNe and CSM environments many years after outburst have been observed in a number of SNe. Of these, SN 1979C is notable in that it is one of the few that we have been able to follow its optical evolution for almost three decades after outburst.

In Figure 2, we show a comparison of optical spectra of SN 1979C spanning ages 11–29 yr after outburst. Overall, these spectra do not show dramatic changes in the overall strength of the emission lines. This is similar to that seen in SN 1979C's X-ray flux which shows no significant decline since SN 1979C was first detected in 1995 (Immler et al. 2005).

However, noticeable changes in the relative strength of the emission lines are observed. These changes are highlighted in Figure 3, which is an overplot of the two MMT observations of SN 1979C at t = 14 and t = 29 yr. Although the flux for each observation is only accurate within ±20%, a decline in the ratio of Hα/[O I] emission is apparent, which agrees with our estimated ∼ 35% decline in Hα emission from 1993. The plot also illustrates how the [O II] and [O III] line profiles display an increase in blueshifted emission centered about −4300 km s^{-1} such that the blueshifted emission dominates over emission near zero velocity at the present epoch.

The position of the blueshifted emission peaks in the forbidden oxygen lines also appears to have shifted over time. In Figure 4 we show the emission line profiles of the [O I] λλ6300, 6364 and [O II] λλ7319, 7330 lines at all four epochs. As seen in this figure, although the total width of the line profiles has not changed significantly, the separation between the two blueshifted emission peaks appears to have decreased with time. That is, the more blueshifted emission peak in both the [O I] and [O II] line profiles has moved toward less blueshifted velocities between 1991 and 2008 (i.e., ages 11 to 29 yr). On the other hand, while a wavelength change for the lower velocity blueshifted peak around −1000 km s^{-1} is more uncertain, the [O I] line profile peaks in the 2008 spectrum suggest an increased blueshift.

Included along the bottom of Figure 4 are the estimated velocities of the more blueshifted [O I] and [O II] peaks (the left and right panels) plotted against the age of the SN. These plots suggest a sharp drop in the velocity of the bluer emission peak between 1990 and 1993 and then a relatively slow decline from 1993 to 2008. During the last 18 years, the blue peak has shifted to the red by some 1400 km s^{-1}.

A similar shift over time of the bluer [O II] emission peak to lower velocities was also observed in SN 1986J (Milisavljevic et al. 2008). In that case, the phenomenon was attributed to the progression of the reverse shock inward toward slower moving O-rich ejecta. The same situation may apply to SN 1979C. Interpreted in this way, the decrease in velocity of the bluer emission peak from 5700 km s^{-1} at $t = 11.1$ yr to 4300 km s^{-1} at $t = 29.0$ yr represents the advance of the reverse shock and can be used to estimate the ejecta density profile. If the density of the SN ejecta, $\rho_{\rm ej}$, as a function of radius r follows the form $\rho_{\rm ej} \propto r^{-n}$, the velocity of the ejecta at the reverse shock, v, should depend on time t as $v \propto t^{-1/(n-2)}$ provided $n > 5$ (Chevalier & Fransson 2003 and references therein). The 1400 km s^{-1} shift over epochs 11.1–29.0 yr years implies a value

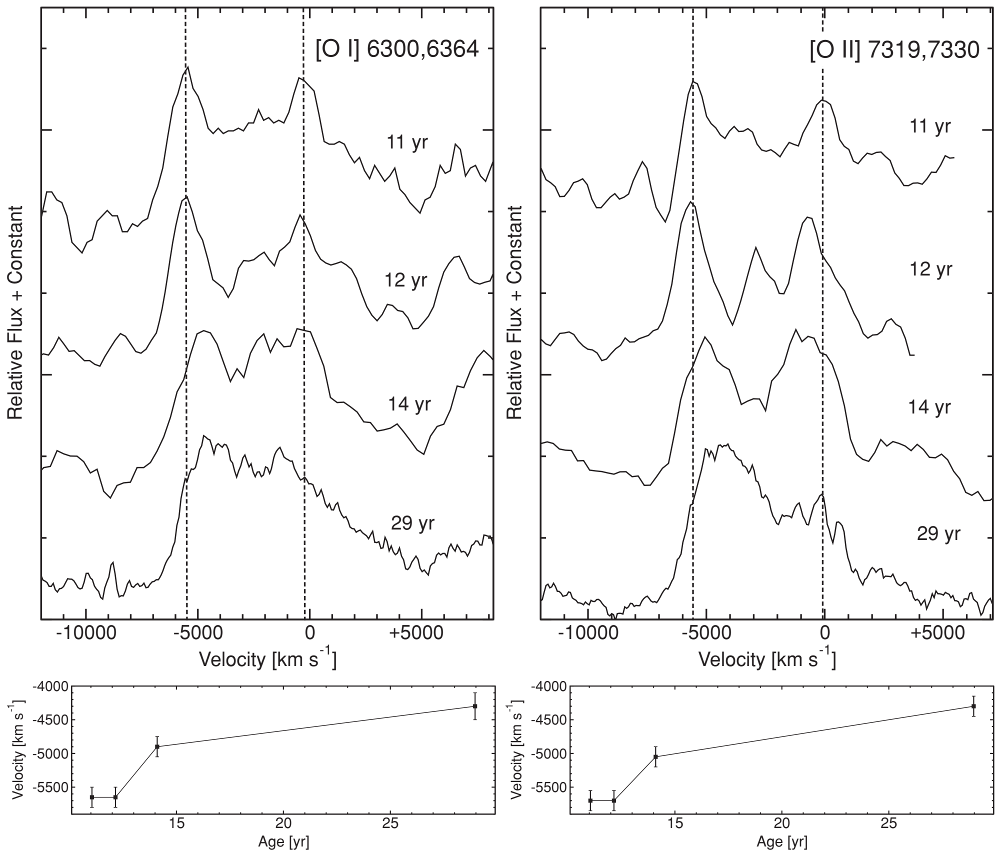

Figure 4. Evolution of forbidden oxygen emission line profiles of SN 1979C. Top: the [O I] λλ6300, 6364 and [O II] λλ7319, 7330 lines at four epochs. Velocities are with respect to 6300 and 7325 Å in the rest frame of NGC 4321. The dashed vertical lines mark the velocities of the emission peaks at the earliest epoch. Bottom: plots of the velocity of the emission peak of greatest blueshift against approximate age of SN 1979C.

Table 1
Type II SNe with Late-time Oxygen Emission Peaks

Supernova	Age (yr)	Emission Peaks ($km\ s^{-1}$)		Lines Observed [O I]	[O II]	[O III]
SN 1970G (1)	22	−5700	···	X		
SN 1979C (2), (4)	12	−5700	−200	X	X	X
	14	−4900	−600	X	X	
	29	−4300	−1000	X	X	X
SN 1980K (3), (4)	12	−3300	−700	X	X	
	16	−3500	−1000	X	X	
SN 1986J (5), (6)	6	−3500	−1000	X	X	X
	24	···	−600	X		

References. (1) Fesen (1993); (2) Fesen & Matonick (1993); (3) Fesen & Matonick (1994); (4) Fesen et al. (1999); (5) Leibundgut et al. (1991); (6) Milisavljevic et al. (2008).

of $n = 5.5$, consistent with this scenario but only marginally so. A greater value of $n = 6.8$ is implied if only the 1993 and 2008 MMT data are considered.

4.2. Blueshifted Oxygen Emission

Blueshifted oxygen emission profiles with one or more emission peaks like those observed in SN 1979C appear to be a common and long-lasting phenomenon in the spectra of several Type II SNe which exhibit bright late-time X-ray, optical, and radio emissions. Table 1 lists three other Type II SNe which have late-time oxygen emission lines displaying two blueshifted emission peaks like those seen in SN 1979C. As can be seen in the table, these four SNe show blueshifted emission peaks, one around a velocity of −200 to −1000 km s^{-1}, and a second, bluer peak at −3300 to −5700 km s^{-1}. Finding four Type II SNe with strongly blueshifted, double-peaked oxygen emissions is interesting and may point to a common, late-time emission property.

On the other hand, some other Type II SNe show quite different oxygen emission profiles from those of SN 1979C, indicating a range of late-time emission properties of O-rich ejecta. For example, SN 1993J at $t \sim 5$ yr showed a "horned" profile in its [O I], [O II], and [O III] lines with strong redshifted emission peaks roughly matching the velocity of the blueshifted peaks (Matheson et al. 2000a, 2000b). Alternatively, other late-time Type II SNe exhibit three or more oxygen emission peaks at both blue and redshifted velocities (e.g., SN 1996cr; Bauer et al. 2008) or just blueshifted oxygen emission lacking high-velocity emission peaks (e.g., SN 1957D and SN 1986E; Cappellaro et al. 1995).

Bridging this diversity of late-time emission properties is the indication that strongly blueshifted line profiles appear to be common in late-time, Type II SN spectra even when double or multiple emission peaks are not present. The commonality of strongly blueshifted oxygen emission in radio and optically bright Type II SNe suggests that they may share similar properties in the distribution of their reverse shock heated O-rich ejecta due to interaction with the surrounding CSM environment, and implicates the presence of dust blocking emission from the rear expanding hemisphere.

We note that spectra of core-collapse SNe just entering the nebular phase ($t > 100^d$) often show double-peaked emission profiles in the lines of [O I] λλ6300, 6364 (Modjaz et al. 2008;

Maeda et al. 2008). Such profiles have been interpreted as due to ejecta expanding with a torus or disklike geometry. However, these double-peaked profiles sometimes have both blue and redshifted velocities centered about the [O I] λ6300 line. Thus, the double-peak emission phenomenon in the late-time spectrum of SN 1979C and other Type II SNe appears different and may not be directly related.

4.3. The Progenitor's Stellar Environment

Lastly, we address the significance of the suspected WR star emission "bump" in the SN 1979C spectrum. *HST* imaging shows the presence of a star cluster in the vicinity of the SN (van Dyk et al. 1999; Immler et al. 2005). As can be seen in Figure 1, our spectrum suggests the presence of a broad emission bump centered around 5800 Å resembling the so-called "yellow" WR emission feature seen in WC-type stars. The lack of strong He II λ4686 emission in the spectrum is also consistent with WC- rather than WN-type WR stars in the SN 1979C star cluster.

Several metal-rich H II regions in M100 have been observed to possess WR stars (Pindao et al. 2002). Analysis of the *HST* imaging data shows the SN 1979C cluster contains young blue stars of ages 4–6 Myr, consistent with the ages of WC stars (van Dyk et al. 1999; Massey 2003). Photometry of the cluster's stellar population yielded an estimate of the progenitor star's initial mass to be (17–18) $\pm$ 3 $M_{\odot}$. Assuming the SN 1979C progenitor was among the more massive stars in its star cluster, our detection of WR-type emission features from this cluster is consistent with such high mass estimates for the SN 1979C progenitor.

5. CONCLUSIONS

We present an optical spectrum of SN 1979C taken almost three decades after outburst. This spectrum is compared against archival spectra to follow the evolution of SN 1979C's late-time optical emission. Overall, Hα emission appears to have decreased by some 35% while the [O I], [O II], and [O III] lines show noticeable increases in blueshifted emission from levels observed in 1993. The separation between emission peaks in the line profiles of [O I] λλ6300, 6364 and [O II] λλ7319, 7330 has decreased over the past 18 years, with the more blueshifted peak's velocity changing from -5700 km s^{-1} to -4300 km s^{-1}. We note that SN 1979C's late-time oxygen line emissions appear similar to other Type II SNe observed 5–30 yr past outburst in that they show largely blueshifted emission, often with a blueshifted, double-peaked line profile. The commonality of these late-time emissions may signal a shared geometry in the oxygen ejecta and/or CSM environment for X-ray, optical, and radio bright core-collapse SNe.

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