Near-Infrared and Optical Observations of Type Ic SN 2021krf: Dust Formation and Luminous Late-time Emission

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ABSTRACT

We present near-infrared (NIR) and optical observations of the Type Ic supernova (SN Ic) SN 2021krf obtained between days 13 and 259 at several ground-based telescopes. The NIR spectrum at day 68 exhibits a rising K-band continuum flux density longward of \( \sim 2 \mu m \), which is likely from freshly formed dust in the SN ejecta. We estimate a carbon-grain dust mass of \( \sim 2 \times 10^{-5} M_\odot \) and a dust temperature of \( \sim 900-1200K \) associated with this rising continuum and suggest the dust has formed.
in SN ejecta. Utilizing the one-dimensional multigroup radiation hydrodynamics code STELLA, we present two degenerate progenitor solutions for SN 2021krf, characterized by C-O star masses of 3.93 and 5.74 $M_\odot$, but with the same best-fit $^{56}$Ni mass of 0.11 $M_\odot$ for early times (0–70 days). At late times (70–300 days), optical light curves of SN 2021krf decline substantially more slowly than that expected from $^{56}$Co radioactive decay. A late-time optical spectrum on day 259 shows strong Ca II and [O I] ejecta lines from the SN. Lack of H and He lines in the late-time SN spectrum suggests the absence of significant interaction of the ejecta with the circumstellar medium. We reproduce the entire bolometric light curve with a combination of radioactive decay and an additional powering source in the form of a central engine of a millisecond pulsar with a magnetic field smaller than that of a typical magnetar.

Keywords: core-collapse supernovae; Type Ic supernovae; individual – SN 2021krf

1. INTRODUCTION

The significance of core-collapse supernovae (CCSNe) as major dust factories in the early universe has been the subject of a long-standing debate. Dust formation in the early universe is implied by the large amount of dust observed in high-redshift ($z$) galaxies (Isaak et al. 2002; Bertoldi et al. 2003; Laporte et al. 2017; Fudamoto et al. 2021). While most of the dust observed in present-day galaxies is considered to originate from stellar winds of asymptotic giant branch (AGB) stars (e.g., Gehrz 1989; Draine 2009; Matsuura et al. 2009), such stars would not be significant contributors to the high-$z$ dust, as the universe was too young for AGB stars to have formed (Morgan & Edmunds 2003; Dwek & Arendt 2008). On the other hand, CCSNe can occur several million years after their massive progenitor stars form. Several young remnants of these types of supernova (SN) explosions have been confirmed to create dust in their ejecta, such as Cas A (Rho et al. 2008, 2012; De Looze et al. 2017), SN 1987A (e.g., Suntzeff & Bouchet 1990; Matsuura et al. 2015), G54.1+0.3 (Rho et al. 2018), and the Crab Nebula (Gomez 2013). This suggests that CCSNe can be a viable source of significant dust formation in the early universe.

CCSNe are classified as Type Ic when their spectra do not obviously exhibit either H and He spectral lines (e.g., Filippenko 1997; Gal-Yam 2017; Williamson et al. 2019). These SNe are thought to be explosions of massive stars that have lost their H envelope and most, if not all, of their He envelope. Considerable controversy exists over the interpretation of the absence in some CCSNe of optical He lines, especially regarding whether that is evidence for He deficiency in the ejecta (Dessart et al. 2011; Hachinger et al. 2012). There are potentially promising He lines in the near-infrared (NIR), and thus observing both the optical and NIR spectra of SNe Ic for He signatures is crucial for understanding the properties of stripped-envelope CCSN progenitors.

SNe Ic are generally believed to be powered by radioactive decay of $^{56}$Ni and its decay product, $^{56}$Co (Colgate & McKee 1969). For a typical SN Ic, the decay of luminosity at late times ($t > 100$ days) is expected to be at least as rapid as the characteristic decay of $^{56}$Co (see Anderson 2019 for a discussion of stripped-envelope SN nickel masses). The late-time luminosity of SNe Ic could be greater than the radioactive decay rate, if the SN had additional power sources such as late-time interactions with circumstellar material (CSM) or interstellar material (ISM), and/or energy input from a central engine (e.g., Ben-Ami et al. 2014; Taddia et al. 2019, who noted late-time CSM interactions and energy from a central engine in SN 2010mb and iPTF15dtg, respectively).

Rapidly rotating neutron stars are believed to be remnants of CCSNe. The observed light curves of some of these SNe could be affected by the spin-down of remnant neutron stars as their rotational energy is released in the form of relativistic magnetized winds (e.g., Kasen & Bildsten 2010; Dessart et al. 2012). The effects of such a central engine may be negligible in the early-epoch SN light curves when the energy from radioactive decay of $^{56}$Ni would dominate the SN luminosity. However, over longer times as the radioactive decay powers down, their contributions may become significant, affecting the evolution of their late-time light curves (e.g., Kotera et al. 2013).

In this work, we report the results of our observations of the recently discovered Type Ic SN 2021krf based on our multi-epoch NIR spectroscopy using the Gemini North Telescope and the NASA Infrared Telescope Facility (IRTF), and optical photometry and spectroscopy from the Las Cumbres Observatory (LCO), the Keck-II 10 m telescope, the Southern Astrophysical Research Telescope (SOAR), and the 3 m Shane telescope at Lick.
We find a rising NIR continuum due to emission from warm dust and a probable detection at day 68 of CO overtone-band emission, and discuss the implications of these for dust formation in SNe. We also present and discuss our spectrophotometric data spanning the first ~300 days after the SN explosion. We find late-time (t > 200 days) flux excesses above those expected from radioactive decay in the light curves of SN 2021krf. We consider several scenarios for additional power sources.

In Section 2, we describe our observations, and in Section 3, we present our results and analysis of the optical photometry and (11 sets of) spectroscopy spanning from the explosion to 350 days, and NIR spectroscopy obtained at 13, 43, and 68 days. Section 4 discusses the origin of the dust emission, optical spectral modeling, dynamic motion of SN ejecta, and hydrodynamic modeling of radioactive decay, and whether additional input energy from a magnetar is required to fit the bolometric light curve. Our conclusions are presented in Section 5.

2. OBSERVATIONS

SN 2021krf (ZTF21aaxtctv) was first detected by the Zwicky Transient Facility (ZTF; Bellm et al. 2019; Masci et al. 2019; Graham et al. 2019) on 2021 April 30 (MJD 59330) at $m_g = 18.0035$ mag (Munoz-Arancibia et al. 2021). Here we assume that the explosion date of SN 2021krf ($t_0$) was 2021 April 26 (MJD 59334.1), which is the midpoint between the ZTF first discovery date (MJD 59334) and its last date of nondetection, 2021 April 21 (MJD 59328). SN 201krf is located in the nearby galaxy 2MASX J12511712+0031138 at a distance of $\approx 65$ Mpc based on NED (NASA/IPAC Extragalactic Database (NED) 2019, assuming $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.308$, $\Omega_{\text{vac}} = 0.692$) with redshift $z = 0.01355$. Based on spectral data from the New Technology Telescope (NTT), it was classified as a Type Ic SN (Paraskeva et al. 2021). We observed SN 2021krf at optical and NIR wavelengths as summarized in Table 1.

2.1. Spectroscopy

We obtained NIR (0.8–2.5 μm) spectra of SN 2021krf with the Gemini Near-Infrared Spectrograph (GNIRS) on the 8.1 m Frederic C. Gillett Gemini North telescope, on 2021 June 8 and 2021 July 3 (UTC dates are used throughout this paper), as part of observing program GN-2021A-Q-126. Exposure times associated with these epochs were 6×300 s and 4×300 s, respectively. Unfortunately, the total integration time for the observation on 2021 July 3 was only 20 min because that was the time left in our program. The short exposure produced a relatively low signal-to-noise ratio (SNR) spectrum above 2.3 μm. We configured GNIRS in the cross-dispersed mode, utilizing a 32 line mm$^{-1}$ grating and a 0′45-wide slit to achieve a resolving power of $\sim 1200$ (250 km s$^{-1}$). Standard stare/nod-along-slit mode (ABBA) with a nod angle of 3′′ was used for the observations. To minimize differences in the airmass, we used nearby early type-A dwarf stars, observed either just before or after SN 2021krf, as telluric and flux standards.

We performed data reduction utilizing both of the GNIRS cross-dispersed reduction pipeline (Cooke & Rodgers 2005) and a manual, order-by-order reduction for the shortest-wavelength orders. We used manual reduction with standard IRAF (Tody 1986) and Figaro (Shortridge et al. 1992) tools for flatfielding, spike removal, rectification of spectral images, extraction, wavelength calibration, and removal of hydrogen absorption lines in the spectra of the standard stars. For order-by-order reduction, spectral segments covering different orders were stitched together after small scaling factors were applied, to produce final continuous spectra between 0.81 and 2.52 μm. As an additional check, similar spectra were also obtained with XDGNIRS, a PyRAF-based data-reduction pipeline (Mason et al. 2015). The standard ABBA method was used to perform sky subtraction and combining with the two-dimensional (2D) data, before final 1D spectral extraction. We note that the observed spectra in the 1.35–1.45 μm and 1.80–1.95 μm bands are affected by the relatively low atmospheric transmission, warranting caution for the reliability at these wavelengths.

We observed SN 2021krf with the short cross-dispersion (SXD) mode of the SpeX spectrograph (Rayner et al. 2003) on the NASA InfraRed Telescope Facility (IRTF) on 2021 May 9. In this mode with the 0′8′′ slit, the spectral resolving power is $R \approx 1000$. Similar to the GNIRS observations, the SN was observed in an ABBA dithering pattern with an A0V star observed immediately before and the associated flatfield- and comparison-lamp observations observed after. We reduced the data using spextool (Cushing et al. 2004), which performed flatfielding, wavelength calibration, background subtraction, and spectral extraction. We then performed telluric correction using xtellcor (Vacca et al. 2003).

We obtained 8 sets of optical spectra at the LCO with the FLOYDS spectrographs mounted on the 2 m Faulkes Telescope North (FTN) at Haleakala (USA) and the identical 2 m Faulkes Telescope South (FTS) at Siding Spring (Australia), through the Global Supernova
Project (Howell 2019), between 2021 May 8 and 2021 July 6. A 2′′-wide slit was placed on the target at the parallactic angle (Filippenko 1982). We extracted, reduced, and calibrated 1D spectra following standard procedures using the FLOYDS pipeline (Valenti et al. 2014).

We obtained optical spectra with the Kast spectrograph (Miller & Stone 1993) on the 3 m Shane telescope at Lick Observatory on 2021 May 10 and 2021 June 4. The spectra were reduced using a custom data-reduction pipeline based on the Image Reduction and Analysis Facility (IRAF) (Tody 1986). The pipeline performed flatfield correction using observations of a flatfield lamp. The instrument response function was derived using observations of spectroscopic standard stars observed on the same night. The 2D spectra were extracted using the optimal extraction algorithm (Horne 1986).

We observed SN 2021krf with the Deep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the Keck-II 10 m telescope on 2022 January 9. We used the 600ZD grating, GG455 order-blocking filter, and 1′′ slit, integrating for $2 \times 1500$ s. The approximate air-mass was 1.27 during the observation, and we aligned the instrument to the parallactic angle. We also observed the spectrophotometric standard Feige110 on the same night and in the same instrumental setup, which was used to derive the sensitivity function and flux calibration described below.

All DEIMOS data reductions were done with pypeit (Prochaska et al. 2020), which performs image-level calibration using the DEIMOS overscan region for bias correction and flatfielding using dome-flat frames, skyline subtraction, and trace fitting and extraction. We then derived a sensitivity function using the extracted spectrum following the usual steps making use of custom IRAF reduction scripts. These steps included bias subtraction, flatfielding, wavelength calibrations using Hg-Ar-Ne lamps, optimal extraction, and flux calibration using a sensitivity curve from a flux standard star observed on the same night as the SN spectrum.

We observed SN 2021krf with the Deep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the Keck-II 10 m telescope on 2022 January 9. We used the 600ZD grating, GG455 order-blocking filter, and 1′′ slit, integrating for $2 \times 1500$ s. The approximate air-mass was 1.27 during the observation, and we aligned the instrument to the parallactic angle. We also observed the spectrophotometric standard Feige110 on the same night and in the same instrumental setup, which was used to derive the sensitivity function and flux calibration described below.

The pipeline is publicly accessible at https://github.com/msiebert1/UCSC_spectral_pipeline.

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**Table 1. NIR and Optical Spectroscopy of SN 2021krf**

| Date         | MJD   | Day | Telescope–Instrument |
|--------------|-------|-----|----------------------|
| 2021 April 26 | 59330 | 0 (= $t_0$) | ... |
| 2021 May 8   | 59342 | 12  | FTN–FLOYDS           |
| **2021 May 9** | 59343 | 13  | IRTF–SpeX            |
| 2021 May 10  | 59344 | 14  | Shane 3 m–Kast       |
| 2021 May 11  | 59345 | 15  | FTN–FLOYDS           |
| 2021 May 17  | 59351 | 21  | FTS–FLOYDS           |
| 2021 May 26  | 59360 | 30  | FTS–FLOYDS           |
| 2021 June 4  | 59369 | 39  | Shane 3 m–Kast       |
| 2021 June 5  | 59370 | 40  | FTS–FLOYDS           |
| **2021 June 8** | 59373 | 43  | Gemini–GNIRS         |
| 2021 June 13 | 59378 | 48  | FTS–FLOYDS           |
| 2021 June 21 | 59386 | 56  | FTS–FLOYDS           |
| **2021 July 3** | 59398 | 68  | Gemini–GNIRS         |
| 2021 July 6  | 59401 | 71  | FTS–FLOYDS           |
| 2021 July 12 | 59407 | 77  | SOAR–Goodman         |
| 2022 January 10 | 59589 | 259 | Keck–DEIMOS         |

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*a* The estimated explosion date, 2021 April 26, is taken to be the middle point between the last nondetection reported by ZTF (2021 April 21) and the first detection (2021 April 30).

**b** NIR observations are marked in bold.

**c** Spectrophotometry of GNIRS spectra on 2020608 and 20210703 yield the following approximate magnitudes: $J$, $H$, $K = 16.3$, 16.0, 16.1, and 16.8, 16.4, 16.5mag, respectively.
standard-star spectrum and applied this to the SN 2021krf spectra. Finally, we coadded the calibrated 1D spectra.

2.2. Photometry

We performed optical photometry ($U, B, g, V, r,$ and $i$ filters) of SN 2021krf with follow-up LCO observations utilizing a world-wide network of telescopes under the Global Supernova Project (Howell 2019). Point-spread-function (PSF) fitting for the images was performed utilizing a PyRAF-based photometric reduction pipeline, lcogtsnpipe\(^3\) (Valenti et al. 2016). When the pre-SN images are not available from the LCO network in $g, r,$ and $i$, we used the $gri$-band Sloan Digital Sky Survey (SDSS; SDSS Collaboration 2017) templates for image subtraction using PyZOGY (Guevel & Hosseinzadeh 2017), an implementation in Python of the subtraction algorithm described by Zackay et al. (2016). The subtracted $gri$ images utilizing SDSS templates were calibrated to AB magnitudes (Oke & Gunn 1983). For $U, B,$ and $V$, LCO images taken respectively on 2022 January 14 ($MJD = 59593$), 2022 March 10 ($MJD = 59648$), and 2022 February 17 ($MJD = 59627$) were chosen as templates for difference imaging. The subtracted $UBV$ data were calibrated to Vega magnitudes. We obtained additional photometric data using the $gr$-band public ZTF data. We used the same pre-SN $gr$ images from SDSS as templates for ZTF difference imaging.

3. RESULTS

3.1. Optical Light Curves and Explosion Properties

The optical light curves of SN 2021krf are shown in Figure 1. Based on ZTF follow-up observations of SN 2021krf, the $g$ and $r$ light curves gradually rise over the first $\sim 10–20$ days. The $r$ light curve peaks at 24.21 days ($MJD = 59354.21$) after $t_0$, with an observed magnitude of 16.67 mag. Because of a gap between ZTF and LCO start dates, the $UBV_i$ light curves that start $\sim 12$ days after the SN rise only marginally before peaking. For example, the $V$ light curve peaks at 20.17 days ($MJD 59348.17$) after $t_0$, with an observed magnitude of 16.76. The maximum $g$ brightness ($g_{\text{max}}$) is at 13.40 days ($MJD = 59343.40$) after the SN explosion, with an observed magnitude of 17.12. As the $U$ light curve decays significantly more rapidly compared with $BgVri$ and there are only four detection epochs, a reliable shape of its light curve could not be determined. We present the $U$ light curve only for completeness, and it is not used in the analysis owing to these issues.

We compare the evolution of the $r$ light curve of SN 2021krf with those of some other SNe Ic in Figure 2. The photometry of the other SNe was obtained from the Open SN catalog (Guillochon et al. 2017). Around the peak, the light curve of SN 2021krf is broader than that of some of the typical SNe Ic such as SN 1994I (Richmond et al. 1996), SN 1998bw (Galama et al. 1998), SN 2004aw (Taubenberger et al. 2006), SN 2007gr (Hunter et al. 2009), SN 2011bm (Valenti et al. 2012), and SN 2020oi (Rho et al. 2021). The SN 2021krf light curve in $r$ declines by $\sim 1.2$ mag between days 25 and 60 (Figure 2). A broad SN Ic light-curve width indicates a relatively low $E_k/M_e$, where $E_k$ is the ejecta kinetic energy and $M_e$ is the ejecta mass (Dessart et al. 2016). The extremely rapidly declining light curves of SN 2020oi and SN 1994I imply low ejecta masses (Filippenko et al. 1995; Rho et al. 2021). The more moderately declining light curve of SN 2007gr is also less broad compared to SN 2021krf. In contrast, the SN 2011bm and iPTF15dtg

\(^3\)https://github.com/LCOGT/lcogtsnpipe
Figure 2. Optical light curve of SN 2021krf in r (solid red circles) compared with r-band light curves of other SNe Ic. The light curves of other SNe are scaled to match that of SN 2021krf at its peak. The $^{56}$Co decay rate is shown as a dashed line, scaled to the SN 2021krf light curve. The late-time light curve of SN 2021krf is above the $^{56}$Co decay rate, implying the existence of an additional power source.

light curves around their peak are broader than that of SN 2021krf.

SN 2021krf exhibits flat light curves at late times ($t > 200$ days) as shown in Figure 1. A normal SN Ic is expected to decline at least as rapidly as the $^{56}$Co radioactive decay rate (see, e.g., Wheeler et al. 2015), which is marked as a dashed line in Figure 2. The SN 2021krf r-band light curve is flatter than the corresponding $^{56}$Co decay line and that of other SNe such as SN 1994I and SN 2007gr (except iPTF15dtg) in Figure 2. Taddia et al. (2019) showed that radioactivity along with magnetar powering is the most realistic explanation for the flat late-time light curve observed for iPTF15dtg. Thus, SN 2021krf (like iPTF15dtg) may have additional power sources such as a central engine or CSM interaction.

To study the pre-explosion properties of the progenitor of SN 2021krf and the explosion kinematics, we compared the observed $BgVri$ light curves from the LCO network and ZTF with theoretical SN nucleosynthesis models obtained using the 1D multigroup radiation hydrodynamics code STELLA (Blinnikov et al. 1998, 2000, 2006). The STELLA code calculates the spectral energy distributions (SEDs) at every time step utilizing a predictor-corrector high-order implicit scheme for line emission. STELLA implicitly solves the time-dependent radiation transfer equation coupled with hydrodynamics. Individual filter light curves are obtained by convolving the corresponding filter response with the simulated SEDs.

In general, carbon-oxygen (C-O) SN progenitors, formed through losses of their hydrogen and helium envelopes, are triggered by Fe-core collapse, creating SNe Ic. Implementing the methodology of Yoon et al. (2019), we utilize two C-O progenitor models to reproduce multicolor light curves of SN 2021krf and derive its explosion parameters. The first SN model (Model CO-3.93 in Table 2) adopts a helium-poor C-O progenitor mass of 3.93 M$_\odot$ while the initial (zero age main sequence; ZAMS) mass of the progenitor is assumed to be $\sim 20$ M$_\odot$. The adopted mass cut where the SN energy is injected in mass coordinates for CO-3.93 is 1.44 M$_\odot$, which corresponds to the outer boundary of the iron core. The second model (Model CO-5.74 in Table 2) assumes a helium-poor C-O progenitor mass of 5.74 M$_\odot$ while the initial mass of the progenitor is assumed to be $\sim 30$ M$_\odot$. The adopted mass cut where the SN energy is injected in mass coordinates for CO-5.74 is 1.66 M$_\odot$.

Using model CO-3.93 to fit the observed light curves, the best-fit kinetic energy ($E_k$) is $0.5 \times 10^{51}$ erg. The best-fit $^{56}$Ni ($M_{Ni}$) and ejecta ($M_{ej}$) masses are 0.11 M$_\odot$ and 2.49 M$_\odot$, respectively. We obtained similarly good fits with the second model CO-5.74, where the best-fit kinetic energy, $^{56}$Ni mass, and ejecta mass are $E_k = 1.05 \times 10^{51}$ erg, $M_{Ni} = 0.11$ M$_\odot$, and $M_{ej} = 4.08$ M$_\odot$, respectively. In these models, we assume that $^{56}$Ni is uniformly mixed throughout 90% of the inner ejecta.

Comparisons between the observed and model light curves are presented in Figure 3. Together, these models provide good fits to the observed light curves until $\sim 40$ days. Beyond this period, the radioactive decay hydrodynamic models significantly underestimate the observed light curves. Our radiation-hydrodynamics modeling with STELLA confirms that standard radioactive decay alone cannot adequately fit the observed light curves across all bands at $t > 40$ days (Figure 3).

Between days 80 and 100 after the SN explosion, the light curves in several bands ($g$, $V$, $r$, $i$) seem to show a marginal rise or bump-like feature. Similar postmax-
Figure 3. STELLA light-curve model fits to the observed optical light curves of SN 2021krf. Two STELLA progenitor models, (a) CO-3.93 and (b) CO-5.74, are plotted as continuous lines. Powered by Ni/Co radioactive decay, they significantly underestimate the observed fluxes in all filters after $\sim 40$ days. In both panels, for the latest two $B$ data points, an upper limit is marked owing to high measurement uncertainties.

minimum bumps around 80 to 150 days (for SNe Ic) have been previously noted, such as in SN 2019stc (Gomez et al. 2021). They suggested that the origin of the bump feature is most likely due to a delayed circumstellar interaction with a shell ejected prior to the SN explosion. However, Chugai & Utrobin (2022) argued that the second peak in SN 2019stc might have been caused by variations in the emission due to magnetar dipole field enhancement of an underlying central engine. While the secondary bump in SN 2019stc was prominent ($r = 19.54$ mag) compared to the peak magnitude ($r = 18.74$ mag), the bump-like feature in SN 2021krf (Figure 1) is significantly fainter ($r = 18.06$ mag) compared to the earlier peak magnitude ($r = 16.66$ mag). The origin of such a bump-like feature in the light curve of SN 2021krf might have been due to additional power sources such as CSM interactions or an underlying central engine. However, with a significantly fainter bump-like feature and fewer epochs of our data at these times, we cannot make any clear inferences. We discuss the possibility of CSM interaction in Section 4.1 and possible central-engine powering in Section 4.4.2.

### 3.2. Extinction

The strength of the Na I D $\lambda\lambda 5890, 5896$ absorption doublet is indicative of the amount of dust along the line of sight. For SN 2021krf, no clear absorption dips are observed at these wavelengths (see Figure 5); only
Table 2. Explosion and Progenitor Properties

| References \(^a\) | SNe Ic | SN 2020oi | iPTF15dtg | SN 2007gr | SN 1994F | SN 2021krf | CO-3.93 | CO-5.74 | Arnett model \(^e\) |
|------------------|-------|-----------|-----------|-----------|-----------|-----------|---------|---------|------------------|
| C-O star (M\(_\odot\)) \(^b\) | 9     | 8         | 1, 2, 3, 4 | 5, 6, 7   | 2.1       | 2.1       | 3.93    | 5.74    | ...              |
| Explosion energy \(E_{\text{exp}}\) (10\(^{51}\) erg) | 2.16  | ...       | 1         | 2.1       | 0.6       | ...       | 0.30    | 0.95    | ...              |
| Kinetic energy \(E_k\) (10\(^{51}\) erg) | 1     | ...       | ...       | ...       | 0.67      | 0.29      | 0.50    | 1.05    | 0.73 ± 0.23      |
| Ni mass \(M_{\text{Ni}}\) (M\(_\odot\)) \(^c\) | 0.07  | 0.29      | 0.076     | 0.07      | 0.07      | 0.07      | 0.11    | 0.11    | 0.118 ± 0.007    |
| Ejecta mass \(M_{\text{ej}}\) (M\(_\odot\)) | 0.71  | 3.5       | 1.8       | 0.6       | 2.49      | 4.08      | 2.76    | 0.44    | ...              |
| Progenitor mass (M\(_\odot\)) \(^d\) | 13    | <35       | 28        | 15        | 20        | 30        | 20      | 30      | ...              |

\(^a\) (1) Valenti et al. (2008); (2) Hunter et al. (2009); (3) Mazzali et al. (2010); (4) Crockett et al. (2008); (5) Iwamoto et al. (1994); (6) Sauer et al. (2006); (7) Immler et al. (2002); (8) Taddia et al. (2019); (9) Rho et al. (2021).

\(^b\) C-O star mass is the progenitor mass at the pre-SN stage.

\(^c\) \(^{56}\)Ni mixing throughout 90\% of the inner ejecta assumed.

\(^d\) Zero age main sequence (ZAMS) mass of the progenitor star.

\(^e\) Arnett-model (Arnett 1982) fits to the photospheric-phase bolometric light curve as discussed in Section 4.4.1

Figure 4. Evolution of \(g - i\) color between SN 2021krf and the SNe Ic sample of Stritzinger et al. (2018a) with known low host-galaxy extinctions (SN 2004fe, SN 2005em, and SN 2008hh). Corresponding upper limits of \((B - V)_{+10}\) are 0.72 mag for SN 2008hh, 1.21 mag for SN 2021krf, 1.25 mag for SN 2004fe, and 1.36 mag for SN 2005em. The Type Ic SN 2009dt with high extinction \((B - V)_{+10} = 1.50\) mag) is shown for comparison.

Marginal dip-like features are observed. We estimate the Galactic reddening toward SN 2021krf using the Galactic dust model of Schlafly & Finkbeiner (2011)\(^4\) and obtain \(E(B - V) = 0.0166 ± 0.0004\) mag. A correlation between extinction in the Milky Way and the equivalent width of Na I D lines \((EW_{\text{Na I D}})\) was presented by Poznanski et al. (2012). Based on this empirical relation, the calculated value of \(E(B - V)\) implies negligible absorption in the Na I D doublet (Phillips et al. 2013). This is in agreement with our observations, suggesting low extinction or a small foreground absorption in the direction of SN 2021krf.

In addition to the relation between \(EW_{\text{Na I D}}\) and host-galaxy excess for an extinction estimate, we also compare the color evolution of SN 2021krf with that of well-known SNe Ic where the host extinction is minimal (SN 2004fe, SN 2005em, SN 2008hh – Stritzinger et al. 2018a). Photometry of SN 2004fe, SN 2005em, and SN 2008hh was obtained from Stritzinger et al. (2018b). Based on an \(EW_{\text{Na I D}}\) upper limit of 1.2 Å estimated for SN 2021krf, the corresponding upper limit on the \(B - V\) color at 10 days past \(V\)-band maximum \((B - V)_{+10}\) is 1.22 mag (see Equation 2 of Stritzinger et al. 2018a). Similar upper limits on \(B - V\) for SN 2004fe, SN 2005em, and SN 2008hh are 0.78, 1.35, and 1.25 mag, respectively. The \(B - V\) color evolution of SN 2021krf is evidently comparable to that of other low-host-extinction SNe Ic.

In Figure 4, we show the evolution of the \(g - i\) color of SN 2021krf in comparison with that of SNe having low extinction and a Type Ic SN 2009dt having relatively high extinction \((B - V)_{+10} = 1.50\) mag; Stritzinger et al. (2018a). At \(g_{\text{max}}\), we see that the \((g - i)\) color observed in SN 2021krf \((\sim 0.15\) mag) is between that of SN 2004fe \((\sim 0.01\) mag), SN 2005em \((\sim 0.11\) mag), and SN 2008hh \((\sim 0.31\) mag). It is significantly different from that of SN 2009dt \((\sim 1.09\) mag). Thus, based on both \(B - V\) and \(g - i\) color evolution, SN 2021krf has a host extinction.

\(^4\) https://irsa.ipac.caltech.edu/applications/DUST/
Figure 5. *Left:* Optical spectra of SN 2021krf with the LCO network, Kast spectrograph, SOAR, and Keck-II telescopes (see Table 1) after being corrected for the host galaxy’s redshift ($z = 0.0135$). Fluxes for individual spectra are scaled for the purposes of display. Rest-frame wavelengths of several atomic lines of interest are marked with vertical gray dashed lines. Ca II at 8200 Å represents the blueshifted Ca II NIR triplet. *Right:* Zoom-in view around the Na I D doublet wavelength range of the corresponding unsmoothed optical spectra at the same epochs as the left panel. No significant absorption is identified; only marginal dip-like features are observed.

3.3. **Optical and NIR Spectroscopy**

Figure 5 shows 11 optical spectra of SN 2021krf, taken between 12 and 259 days. Similarly, the NIR spectra taken between 13 and 68 days are shown in Figure 6, along with corresponding optical data from the nearest epochs. Both optical and NIR spectra are corrected for the host-galaxy redshift with the former being expressed in standard temperature and pressure (STP) using angstroms and the latter in vacuum using microns. Rest wavelengths of atomic lines observed in the optical and NIR regimes are from the SN models by Dessart et al. (2012), synthetic spectra using SYNAPPS (Thomas et al. 2011), and other observed spectra of SNe Ic (Gerardy et al. 2002; Hunter et al. 2009; Drout et al. 2016; Jencson et al. 2017; Stevance et al. 2017, 2019).

The optical and NIR spectra of SN 2021krf are dominated by atomic lines in absorption, emission, and mixed
Figure 6. NIR Spectra of SN 2021krf from IRTF-SpeX and Gemini-GNIRS (see Table 1) after being corrected for the host galaxy’s redshift ($z = 0.0135$). Optical spectra at epochs closest to the corresponding NIR epochs are included. Dashed line (blue) in the day 68 spectrum represents the approximate $K$-band continuum. Rest-frame wavelengths of several atomic lines of interest are marked with vertical gray dashed lines. Possible minor contributions from He I lines are marked as brown dotted lines.

Contributions in the form of P Cygni profiles. The strongest absorption feature in the optical spectra is marked as Ca II at 8200 Å (in Figure 5), which contains contributions from the blueshifted NIR Ca II triplet ($\lambda = 8492, 8542, \text{and } 8662$ Å). The optical spectra do not reveal any clear indication of He I lines. Several Fe II lines appear $\sim 21$ days after the SN around 4233, 5169, 5364, and 5355 Å. The Na I doublet (at 5899 Å) first appears $\sim 40$ days after the SN and increases in strength thereafter. Similar evolution of several other emission lines (e.g., [O I], Ca II, O I/Mg II) is also evident (Figure 5). Clear [O I] doublet line emission at 6300 and 6364 Å appears in the ejecta starting on day 48 and strengthens by day 71 at the beginning of the nebular phase. [O I] emission is extremely strong at late times ($\sim 259$ days), indicating the existence of significant amount of oxygen ejecta as one would expect from a stripped-envelope SN.

The strongest ionic contributions in the NIR spectra are from Ca II, S I, O I, C I, and Si I (Figure 6). The Ca II NIR triplet shows mixed contributions from
absorption and emission, thus having a P Cygni profile. We adopt a mean wavelength of 0.8567 \( \mu \)m for this triplet. We observe significant absorption at \( \sim 1.04 \mu \)m which could be the blueshifted absorption line of S I at 1.082 \( \mu \)m. Another possible contribution to the absorption is from He I 1.083 \( \mu \)m, which is the strongest He I transition (Swartz et al. 1993) and thus should be sensitive to small quantities of helium (Wheeler et al. 1993; Baron et al. 1996). However, the corresponding He I feature at 2.0581 \( \mu \)m was not detected. Thus, with only weak evidence of He features, we suggest that there is at most a small amount of helium in the SN ejecta. A similar result was previously obtained for SN 2007gr, where a possible small amount of helium was suggested based on NIR line features (Hunter et al. 2009). These observed line profiles along with other lines of [Si I] at 1.129 \( \mu \)m, C I at 1.175 \( \mu \)m, and Mg I at 1.504 \( \mu \)m are similar to those observed in the spectra of other SNe Ic such as SN 2020oi (Rho et al. 2021), SN 2011dh, SPIRITS 15c (Jencson et al. 2017), and SN 2007gr (Hunter et al. 2009).

Longward of 2 \( \mu \)m, the NIR continuum flux density from SN 2021krf increases on day 68. In fact, between day 43 and 68, the slope of the spectrum above 2 \( \mu \)m reversed sign (Figure 6). This change in the NIR continuum shape suggests emission by warm dust. We discuss our spectral modeling of this continuum in Section 3.4. Detection of warm dust at such early times is rare for SNe Ic. We note that a similar detection of warm dust was reported for the Type Ic SN 2020oi at a comparable epoch (Rho et al. 2021).

Figure 7 shows a comparison of SN 2021krf spectra between 2.0 and 2.45 \( \mu \)m with CO bandhead (2-0, 3-1, and 4-2 at 2.293, 2.322, and 2.352 \( \mu \)m, respectively) detections from SN 2020oi (Type Ic) and SN 2017eaw (Type IIP). They are clearly evident in the spectrum of SN 2017eaw at day 124, but are not as obvious in the spectrum of SN 2021krf owing to the low signal-to-noise ratio. However, the SN 2021krf spectrum at day 68 shows local emission around the CO bands, indicating that CO emission is likely present. Considering that the flattening or a rising continuum (evidence of dust formation) is known to occur along with CO cooling as seen in the cases of SN 1987A (Liu & Dalgarno 1995), SN 2017eaw (Rho et al. 2018), and SN 2020oi (Rho et al. 2021), and as expected from theoretical models (e.g., Sarangi & Cherchneff 2013), the corresponding first-overtone CO bands are likely to be present in SN 2021krf.

3.4. Dust Emission in SN 2021krf

The rising continuum probably has contributions due to CO emission (above 2.2 \( \mu \)m) as discussed above. Owing to the lack of a clear, strong detection of these CO features, we assume the features between 2 and 2.4 \( \mu \)m are a combination of both CO and dust continuum, similar to that of another SN Ic, SN 2020oi (Rho et al. 2021).

We have fitted the dust continuum (in the range 2.0–2.3 \( \mu \)m) in SN 2021krf at 68 days (Figure 6) with a modified blackbody model, which is the Planck function, \( B_{\nu}(T) \), multiplied by the absorption efficiency, \( Q_{\text{abs}} \). The continuum we use to fit is similar to the analysis in SN 2020oi (Rho et al. 2021), where we used the three portions of the continuum: 2.01–2.08 \( \mu \)m, 2.155–2.17 \( \mu \)m, and 2.255–2.285 \( \mu \)m. The portions of the continuum exclude the wavelength ranges of CO features.

We assume the dust grains consist of carbon, as they condense early, at temperatures of 1100–1700 K (Fedkin et al. 2010). Three different grain sizes at 0.01 \( \mu \)m, 0.1 \( \mu \)m, and 1.0 \( \mu \)m were considered. We also considered alternate silicate grains such as MgSiO$_3$, as they
condense at temperatures of 1040–1360 K (Speck et al. 2011).

The best continuum-fitting results are shown in Figure 8. Optical constants of the grain species used in the calculation of $Q_{\text{abs}}$ are the same as described by Rho et al. (2018) and references therein. The best-fit temperatures and dust masses are presented in Table 3. Depending on these results and assumed grain species and sizes, we estimate a dust mass between $\sim 5 \times 10^{-6}$ and $2 \times 10^{-5}$ M$_{\odot}$ and a dust temperature range of $\sim 900$–1200 K. Additional cooler dust emitting at wavelengths greater than 2.5 µm cannot be adequately constrained from our data. Thus, our derived dust mass is a lower-limit estimate to the total dust at this phase. We discuss the possible origin of this dust emission in Section 4.1.

4. DISCUSSION

We consider multiple scenarios to explain the origin of dust emission in Section 4.1. Spectral model fits of the optical spectra in the photospheric phase between days 12 and 71 are presented in Section 4.2, and velocity profiles of the observed line features in Section 4.3. Bolometric light-curve modeling and additional power sources are discussed in Section 4.4.1 and Section 4.4.2, respectively.

4.1. Origin of Dust Emission

NIR emission from dust was directly detected on day 68. However, the dust that is responsible for the excess appears to have affected the optical spectrum at earlier times, as discussed below. Possible origins and locations of the dust are (a) formation of dust in the expanding SN ejecta; (b) formation of dust in the dense CSM surrounding the SN; and (c) radiative heating by the SN flash of pre-existing dust in the surrounding CSM/ISM, the so-called “IR echo.”

Dust formation in the SN ejecta: The evolution of emission-line profiles in the nebular phase of the SN ejecta can reveal the presence of newly formed dust. Newly condensed dust may obscure the receding ejecta, suppressing the redshifted component of emission lines and resulting in asymmetric emission-line profiles. Indeed, dominant blue wings on hydrogen and helium emission lines are often observed in CCSNe (Elmhamdi et al. 2004; Smith et al. 2008).

In the stripped-envelope SN 2021krf, strong asymmetry is present in the blended [O I] λ6300, 6364 lines on days 48, 56, 71, 77, and 259 (Figure 5). The emission profiles of this blended line complex are shown in much more detail in Figure 9.

Studies of the [O I] doublet emission lines in stripped-envelope SNe have shown a predominance of blueshifted features (Taubenberger et al. 2009; Milisavljevic et al. 2010). Internal scattering or dust obscuration of the emission from the far-side ejecta were suggested to be the most likely causes of the asymmetry by Milisavljevic et al.. With a sample of 39 SNe Ib/c, Taubenberger et al. favored the opaque-ejecta scenario to explain the observed predominantly blueshifted peaks. Observing the temporal evolution of SN Ib/c [O I] doublet profiles could provide crucial insights into asphericity in the ejecta distribution, the existence of freshly formed dust, or identify effects of an opaque inner ejecta, any of which could result in a lack of redshifted emission.

In order to study the temporal evolution of asymmetry, we integrated the line fluxes on the blue and red sides of the mean wavelength of the doublet on each of days 48, 56, 71, 77, and 259. (Note that the dynamic motion of the oxygen line from day 48 has a relatively constant velocity, which will be discussed in Section 4.3.) The mean wavelength of the doublet is dependent on the relative intensity of the 6300 Å and 6364 Å emission lines. For SN 1987A, the doublet ratio between 6300 Å and 6364 Å ($I_{6300}/I_{6364}$) changed between $\sim 1.3$ at $t = 200$ days to $\sim 2.6$ at $t = 600$ days (Spyromilio et al. 1991). At early times when these lines are optically thick, the expected ratio is close to 1:1, while at late times as the ejecta expand (becoming optically thin), the ratio increases to 3:1 (Li & McCray 1992). We consider these two limiting cases of 1:1 and 3:1, as the epochs between days 48 and 259 are expected to have a ratio between them. The weighted-mean rest wavelengths corresponding to 3:1 and 1:1 are 6320 Å and 6332 Å, respectively. We define “blue flux” as the line-integrated flux to the blue side of the weighted mean and “red flux” as the corresponding line-integrated flux to its red side. The ratios of the blue and red fluxes between days 48 and 259 are presented in Table 4 and Figure 10. The decrease of the flux ratio from day 56 to day 259 is statistically significant. Measurement uncertainties include both the spectral noise in the desired wavelength range and the statistical scatter on the linear fit of the underlying continuum for the [O I] line profile at each epoch.

| Species | Grain size | Temperature | Dust Mass |
|---------|------------|-------------|-----------|
|         | (µm)       | (K)         | ($10^{-5}$ M$_{\odot}$) |
| C       | 0.01       | 900 ± 50    | 2.4 ± 1.1 |
|         | 0.1        | 880 ± 50    | 2.7 ± 1.2 |
|         | 1.0        | 1170 ± 90   | 0.5 ± 0.2 |
| MgSiO$_3$ | 0.1 or 1   | 1020 ± 70   | 2.8 ± 1.2 |

Table 3. Dust species
Figure 8. The best-fit continuum spectral models between 2.0 and 2.3 μm for day 68, fit for C and MgSiO$_3$ dust grains of different grain sizes. The scatter in the unsmoothed data is shown in gray.

Figure 9. Continuum-subtracted [O I] $\lambda\lambda$6300, 6364 line-profile evolution between days 48 and 259. Weighted mean wavelengths of the [O I] doublet assuming the intensity ratio between the 6300 and the 6364 Å components to be 3:1 and 1:1 are marked as blue and orange dashed lines, respectively. Color scheme of the optical spectra is identical to that in Figure 5.

We find that between days 48 and 77, the blue flux is significantly higher than the red counterparts. This suggests that the ejecta moving away along the line of sight toward the rear are obscured, likely owing to the formation of fresh dust. Note that the dust must be located within the [O I] line-emitting region. Maximum asymmetry is noted between days 48 and 56, after which the asymmetry noticeably decreases by day 259. As the ejecta expand, the column density of dust along the line of sight to the SN should decrease, resulting in a decreas-
ing asymmetry of the line profile. This is in agreement with observing much lower asymmetry at day 259.

It is interesting to note that the NIR excess was observed at day 68, in between the days of high observed asymmetry of the [O I] profile (day 48 and 77). Thus, both the optical (maximum blue-red asymmetry) and NIR excess are consistent with dust formation during this time interval. Additional NIR spectra between day 48, when the [O I] line-profile asymmetry was first clearly detected, and day 77, when the asymmetry was still large though decreasing, might have constrained the nature and amount of dust formed in this period. Although contributions from opacity in the inner ejecta and/or geometrical effects of ejecta distribution cannot be ruled out as causes of the observed asymmetry, the concurrence of high asymmetry in the [O I] line profile with the NIR excess suggests that formation of dust in the SN ejecta is a likely candidate.

The rising 2.0–2.5 μm continuum at day 63 of SN 2020oi, another SN Ic, was attributed by Rho et al. (2021) to freshly formed dust in the Si-S layers at a temperature of ~ 810 K and with a dust mass of ~ 6 × 10^{-5} M⊙. Thus, SN 2021krf is the candidate second case of a Type Ic SN showing a rising NIR dust continuum at an early epoch.

**Dust from CSM:** The change in the slope of the K-band continuum may be due to radiative heating of pre-existing circumstellar dust produced by the SN progenitor or by newly formed dust in the swept-up dense CSM. In Type IIn SNe (e.g., SN 2005ip and SN 2006jd), Fox et al. (2009, 2010, 2011) found compelling evidence of continuum emission from warm dust in the dense CSM within ~ 100 days after the explosions. The mass of dust formed in dense CSM knots of the ejecta of these SNe were found to be small as expected, since the mass-loss rate is rather low. The long duration of the NIR excess was interpreted to be due to heating associated with radiative shocks forming at interfaces of the SN-CSM interactions (Fox et al. 2009).

In the case of SN 2005ip, Fox et al. (2010) derived dust temperatures of 900–1100 K and a dust mass of ~ 5 × 10^{-4} M⊙. They suggested that the emission originated either in newly formed dust in the ejecta or in a dense cool circumstellar shell in which pre-existing CSM was being continuously heated by interactions with the ejecta. For the case of SN 2006jd, Stritzinger et al. (2012) estimated a warm-dust mass of (0.7–9.8) × 10^{-4} M⊙. In addition to the possibility of early-time warm dust emission, both SNe 2005ip and 2006jd were found to exhibit thermal emission associated with a colder dust component (T ~ 400–500 K).

This dust emission has been attributed to SN-CSM interactions (Fox et al. 2010, 2011) at later times. Note that Type IIn SNe have clear evidence for the existence of a circumstellar shell showing up as narrow lines of H and He during the early stages of these SNe.

In Figure 11, we compare the late-time optical spectrum of SN 2021krf with nebular-phase spectra of the following SNe Ic: (1) SN 1994I, a spectroscopically typical SN Ic (Filippenko et al. 1995); (2) iPTF15dtg, an SN Ic in which a late-time excess was observed (Taddia et al. 2019), similar to SN 2021krf; and (3) SN 2010mb, a peculiar SN Ic with strong evidence of late-time SN-CSM interactions (Ben-Ami et al. 2014). The CSM interactions are often H and He lines from a circumstellar shell as discussed earlier in the case of SN 2010mb. However, a late-time Keck spectrum of SN 2021krf exhibits strong [O I] and [Ca II] ejecta lines (Figure 5), similar to that of iPTF15dtg, with no line emission from H or He (Taddia et al. 2019). Thus, it is unlikely that at late times there is any ejecta interaction with a H- and He-rich CSM in SN 2021krf.

At wavelengths below ~ 6000 Å, the continuum of SN 2010mb shows a strong blue excess (see Figure 11) and a corresponding slow light-curve decline at late times (Ben-Ami et al. 2014). As its spectrum showed no H lines, Ben-Ami et al. (2014) utilized a H-poor SN-CSM interaction model to fit the unusually strong blue quasicontinuum, thus interpreting it as a product of the interactions of the ejecta with the surrounding CSM. The corresponding slow light-curve decline at late times in SN 2010mb was also attributed to the interaction with a H-poor CSM. Unlike SN 2010mb, nebular spectral signatures of iPTF15dtg and SN 1994I did not show any indicators of circumstellar interaction (Taddia et al. 2019; Sauer et al. 2006). Similar to iPTF15dtg and SN 1994I, SN 2021krf has a significantly weaker blue continuum compared to SN 2010mb, and thus no clear evidence for a H-poor circumstellar interaction at

**Table 4. [O I] Doublet Flux Asymmetry**

| Epoch (days) | Blue Flux / Red Flux (3:1 line ratio) | Blue Flux / Red Flux (1:1 line ratio) |
|--------------|-------------------------------------|-------------------------------------|
| 48           | 3.7 ± 0.4                           | 5.0 ± 0.6                           |
| 56           | 3.7 ± 1.2                           | 5.0 ± 1.1                           |
| 71           | 2.3 ± 0.1                           | 3.2 ± 0.2                           |
| 77           | 2.12 ± 0.01                         | 2.84 ± 0.01                         |
| 259          | 1.192 ± 0.003                       | 1.613 ± 0.004                       |

**Note—** 3:1 and 1:1 are the two limiting line ratios of Doppler-shifted 6300 Å and 6364 Å lines as considered by Li & McCray (1992).
late times. This suggests that the nebular spectrum of SN 2021krf is similar to that of other typical stripped-envelope SNe. Thus, we conclude that CSM interaction is an unlikely explanation for the observed NIR excess in SN 2021krf.

**Thermal IR Echo:** A third possible explanation for the NIR excess observed in SN 2021krf is an IR echo from pre-existing CSM dust. This pre-existing dust is likely formed in the progenitor’s wind. In this scenario, the SN explosion radiatively heats pre-existing dust lying beyond a dust-free cavity, producing an IR echo (see Bode & Evans 1980a,b; Dwek 1983; Emmering & Chevalier 1988). NIR excesses around some SNe IIn have been explained by formation of circumstellar shells, due to IR echoes around them (Dwek 1983; Graham & Meikle 1986). Such circumstellar shells often cause a relatively high extinction toward SNe (Graham & Meikle 1986).

SN 2021krf is a Type Ic SN and has relatively low extinction ($E(B-V) = 0.0166$ mag; see Section 3.2). Moreover, until day 259, the spectra of SN 201krf show no evidence of CSM interaction which could make a dust-free zone for the IR echo. For the NIR excess emission observed at 68 days to be consistent with an IR echo, existence of CSM outside the dust-free cavity should be established. However, in optical spectra at day 71 and thereafter until day 259, no signs of SN-CSM interaction are found (Figure 5 and Figure 11). Because the late-time spectrum (at 259 days) is CSM-free, the dust-free cavity formed by a light echo would have to be at least larger than 259 light days in radius (i.e., ~$10^{17}$ cm). Based on our current observations, this would be a crude lower limit for the cavity size, if an IR echo had produced it. For a massive (20–30 M$_\odot$) W-R progenitor star, the radius of the circumstellar shell is expected to be on the order of $10^{17}$ to $10^{19}$ cm (Garcia-Segura et al. 1996). Additionally, such a cavity would have to be dust-free, whereas the NIR excess in SN 2021krf was found significantly earlier, at day 68. Thus, contributions to the NIR excess by pre-existing dust in the CSM beyond the dust-free cavity through a thermal-IR echo is unlikely.

We conclude that among the three generally observed mechanisms for early-time NIR excesses in CCSN spectra, dust formation in the SN ejecta is the most likely origin of the excess in SN 2021krf. Additional NIR spectra near day 68 would have better constrained the properties of the dust, its evolution, and its origin. IR spectra at later times than reported here are critical to unambiguously understand the dust emission in SNe Ic. The
spectra of SN 2021krf reported here, together with previously published observations of SN 2020oi, confirm early dust formation in SNe Ic. Dust features observed at near- and mid-infrared wavelengths, crucial for advancing our understanding of dust formation, evolution, and destruction in CCSNe, will be investigated at greater detail and to later (fainter) stages of evolution in the era of the James Webb Space Telescope (JWST) and the Extremely Large Telescopes (ELTs).

4.2. Optical Spectral Modeling: Photospheric Phase

The photospheric phase optical spectra of SN 2021krf contain some blended P Cygni lines. A spectral synthesis code is required to identify these features and to examine the chemical and velocity evolution of the object. LCO spectra were modeled at days 12, 21, 40, and 71. We present the best-fit spectral model at these epochs in Figures 12, 13, and 14.

We utilized the SYN++ (Thomas et al. 2011) code, an improved version of the original SYNOW code (Hatano et al. 1999), to model the available photospheric optical spectra of SN 2021krf. This code uses some global parameters: \( a_0 \), a constant normalization parameter to scale overall model flux; \( v_{\text{phot}} \), the photospheric velocity; and \( T_{\text{phot}} \), the photospheric temperature. Other parameters characterize the features of different ions: \( \log \tau \), the optical depth for the reference line of each ion; \( v_{\text{min}} \), the inner velocity of the line-forming region; \( v_{\text{max}} \), the outer velocity of the line-forming region; \( \sigma \), the scale height of the optical depth in the line-forming region in \( \text{km s}^{-1} \); and \( T_{\text{exc}} \), the Boltzmann excitation temperature of each element assuming local thermodynamic equilibrium (LTE). All spectra were corrected for redshift and Milky Way extinction before the fitting. The calculated SYN++ model parameters can be found in Table 5.

The best-fit model of the first spectrum, taken at day 12, shows a photospheric velocity of 10,000 \( \text{km s}^{-1} \), a typical value for SNe Ic at early, pre-maximum phases. The temperature at the photosphere is 8000 K, which is consistent with the spectrum being dominated by lines of neutral and singly ionized elements: C II, N II, O I, Si II, Ca II, Sc II, and Fe II. All features identified with SYN++ are consistent with being photospheric; in fact, no detached or high-velocity features were found at any epoch.

The observed spectrum and best-fit model spectrum associated with the first epoch at day 12 are shown in the left panel of Figure 12. In the right panel, contributions of individual ions to the overall model spectrum are shown. The best-fit model of the second-epoch spectrum, which was taken at day 21, contains the same ions as the pre-maximum model, but with slightly different optical depths (see Table 5, the top panel of Figure 13, and Figure 15). The photospheric velocity and temperature did not change significantly by this epoch.

The bottom panel of Figure 13 displays the modeling of the third spectrum observed at day 40. By this phase the expansion velocity of the photosphere has receded to \( \sim 7000 \text{km s}^{-1} \), and the photospheric temperature has declined from 8000 K to 7000 K. Because of the latter decrease, the N II lines have disappeared from the spectrum, and the O I, Si II, Sc II, Fe II, and C II lines weakened. Only one ion, Ca II, increased in both emission and absorption, compared to the previous epochs.

| Table 5. SYN++ model parameters |
|---------------------------------|
| Parameter                     | 12 d | 21 d | 40 d | 71 d |
| \( v_{\text{phot}} \) (\( \text{km s}^{-1} \)) | 10,000 | 9000 | 7000 | 6000 |
| \( T_{\text{phot}} \) (K)           | 8000 | 8000 | 6000 | 6000 |
| log optical depths             |      |      |      |      |
| Ion               | 12 d | 21 d | 40 d | 71 d |
| C II              | -1.5 | -2.0 | -3.9 | -     |
| N II              | -1.7 | -3.0 | -     | -     |
| O I               | 0.9  | 0.9  | -0.2 | -0.5 |
| Na I              | 0.3  | 0.0  | -1.0 | -1.0 |
| Si II             | 0.5  | 0.0  | -1.5 | -     |
| Ca II             | 0.5  | 1.5  | 2.0  | 1.5  |
| Sc II             | -0.8 | 0.2  | -0.7 | -0.3 |
| Fe II             | 0.4  | 1.2  | 0.2  | -0.3 |
| Feature widths in units of \( 1000 \text{ km s}^{-1} \) |      |      |      |      |
| C II              | 1.0  | 1.0  | 1.0  | -     |
| N II              | 1.0  | 1.0  | 1.0  | -     |
| O I               | 1.0  | 1.0  | 1.0  | 3.0  |
| Na I              | 1.0  | 1.0  | 1.0  | 1.0  |
| Si II             | 1.0  | 1.0  | 1.0  | -     |
| Ca II             | 2.0  | 2.0  | 1.0  | 5.0  |
| Sc II             | 1.0  | 1.0  | 1.0  | 1.0  |
| Fe II             | 1.0  | 1.0  | 1.0  | 1.0  |
| Excitation temperatures in units of 1000 K |      |      |      |      |
| C II              | 8.0  | 8.0  | 6.0  | -     |
| N II              | 8.0  | 8.0  | 7.0  | -     |
| O I               | 8.0  | 8.0  | 6.0  | 6.0  |
| Na I              | 8.0  | 8.0  | 6.0  | 6.0  |
| Si II             | 8.0  | 8.0  | 6.0  | -     |
| Ca II             | 8.0  | 8.0  | 6.0  | 6.0  |
| Sc II             | 8.0  | 8.0  | 7.0  | 6.0  |
| Fe II             | 8.0  | 8.0  | 6.0  | 6.0  |

Note—For all models, \( v_{\text{min}} = v_{\text{phot}} \) and \( v_{\text{max}} = 30,000 \text{ km s}^{-1} \) was assumed.
as can also be seen in the evolution of optical depths of individual ions (Figure 15).

The spectrum taken near the beginning of the nebular phase at day 71 is plotted along with its best-fit model in Figure 14, together with the contributions of individual ions to the overall model spectrum. By this epoch, \( v_{\text{phot}} \) has decreased to 6000 km s\(^{-1}\) and \( T_{\text{phot}} \) to 6000 K. The identified features are due to O I, Na I, Ca II, Sc II, and Fe II. The strengths of these lines have not changed significantly since the previous epoch, except for the Ca II NIR triplet, which has further strengthened. Note that some forbidden transitions, including the \([\text{O I}]\) \( \lambda\lambda 6300, 6364 \) doublet, have started to strengthen, marking the beginning of the nebular phase.

To summarize, based on our optical spectral fitting of the photospheric phase of SN 2021krf, significant temporal changes occurred between days 12 and 71, mainly in the strong absorption due to O I and Ca II ions. The feature at \( \sim 5800 \) Å could also be modeled by the He I \( \lambda5876 \) line instead of the Na I \( \lambda\lambda 5890, 5896 \) doublet. However, the optical He lines are highly blended with many other nearby lines, whereas the NIR He lines (e.g., 2.059 \( \mu \)m) are more isolated. When we examine the He absorption feature at 2.058 \( \mu \)m, there is no clear evidence of this line in SN 2021krf (see Figure 6 and Section 3.3). The evidence for He is even weaker than that discussed in the Type Ic SN 2020oi (Rho et al. 2021). Therefore, we identify SN 2021krf as a Type Ic SN.

### 4.3. Velocity Profiles

Doppler shifted line-velocity measurements based on the SYN++ model fits to the observed optical spectra are presented in Table 6. Based on the spectral models, an uncertainty of 500 km s\(^{-1}\) is estimated for each individual ion line velocity. As all optical spectra have already been corrected for the host-galaxy redshift, the Doppler shift of individual lines is entirely due to kinematics in the SN. Note that these ion velocities are different from the photospheric velocity given by the SYN++ models, as they are calculated simply from the Doppler shift of the absorption minima of the strong features in the spectra, assuming that a particular feature is entirely due to a given ion. Hereafter, we refer to it as ion velocities. However, the changes in the observed spectral features could be due to temporal changes from one atomic line or a blending contribution from several atomic lines. As we have both optical and NIR spectral observations, we use the strong absorption feature produced by the Ca II NIR triplet, observed in both the optical and NIR spectra to independently estimate its velocity.

The velocity profiles of the strong absorption lines of Ca II and O I observed with the optical spectrographs at LCO and SOAR, along with the profiles of the S I line and the same Ca II lines observed with NIR spectrographs, are presented in Figure 16. We estimate an ion velocity of \( \sim 11,000 \) km s\(^{-1}\) from the optical observation at day 12 for the Ca II absorption minimum. As
SYN++ models do not work well with NIR spectra owing to incomplete line lists, we employ simple Gaussian modeling to estimate velocities. Using three Gaussians to fit the NIR Ca II triplet at day 13, we estimate an ion velocity of $10,400 \pm 200 \, \text{km} \, \text{s}^{-1}$ from its absorption minima. This result is consistent with the independently derived optical velocities of $\sim 11,000 \pm 500 \, \text{km} \, \text{s}^{-1}$ for Ca II using SYN++.

The temporal evolution of ion velocities at optical and NIR wavelengths is shown in Figure 17. The lines of O I, Ca II, and Fe II exhibit higher velocities than Si II at the first three epochs (days 12, 21, and 40) when they are detected. This is probably due to the higher optical depths in their lines, which may cause only the outer higher-velocity layers of the homologously expanding ejecta to be observed. Differences between velocities of outer layers for Fe and lighter element such as Si II (Hoflich 1991) could be indicative of asphericities in the ejecta distribution as is evident in some CCSNe (e.g., Mazzali et al. 2001). At NIR wavelengths, both Ca II and S I absorption minima decrease in velocity between days 13 and 68, consistent with a receding photosphere observed at the beginning of the nebular phase.

4.4. Bolometric Light Curve

We constructed a bolometric light curve of SN 2021krf using SuperBOL (Nicholl 2018), which is shown in Figure 18. The input LCO and ZTF photometric magnitudes have been dereddened based on $E(B - V)$ (see Section 3.1) in the direction of SN 2021krf. Photomet-
Figure 16. Evolution of the velocity profiles of the Ca II triplet observed with NIR spectrographs (panel (a)) and the optical spectrographs at LCO and SOAR (panel (b)), the S I 1.082 μm line (panel (c)), and the O I line at 7774 Å (panel (d)). The temporal shift of the absorption minima in panels (b) and (d) are marked with a black dashed line and their associated ion velocities are given in Table 6. The velocities of absorption minima for the NIR Ca II triplet (panel (a)) are marked as red circles at velocities $-10,400, -9900,$ and $-8600$ km s$^{-1}$ at days 13, 43, and 68, respectively. Similarly, for S I ion (panel (c)) at 1.082 μm, the velocities associated with absorption minima are marked as red circles at $-10,100, -10,500,$ and $-9200$ km s$^{-1}$ at days 13, 43, and 68, respectively.

Figure 17. Velocities of some of the identified atomic lines are plotted as a function of time. In panel (a) the velocities were estimated using SYN++ modeling as discussed in Section 4.2 and presented in Table 6. In panel (b), the velocities were measured using multi-Gaussian modeling of the NIR spectra to identify Doppler shifts of the absorption minima from the rest wavelengths.

ric data from all filters (BgVri) were interpolated to a common set of epochs and converted to flux units. We also include JHK photometry at days 43 and 68 (Table 1). Based on these fluxes, SuperBOL computes a quasibolometric light curve by integrating over the range of the observed filters. A blackbody function is fit to the SED, and extrapolated to include the UV contribution to the total bolometric luminosity. Including the NIR photometry greatly constrains the contribution of NIR flux at early times ($t < 100$ days) to the total luminosity. We use the constructed bolometric light curve based on BgVriJHK for our modeling.

4.4.1. Arnett Model Fits

We fit the bolometric light curve with the semi-analytic prescription of Arnett (hereafter the “Arnett
Table 6. Doppler shift velocities (in km s$^{-1}$)

| Age (d) | Ca II 3951Å | Fe II 5169Å | Si II 6355Å | [O I] 7774Å | Ca II 8566Å |
|---------|-------------|-------------|-------------|-------------|-------------|
| 12      | 11500       | 9800        | 7800        | 9800        | 11200       |
| 15      | 11400       | 9600        | 7100        | 9300        | 11000       |
| 21      | 10900       | 8700        | 5500        | 7700        | 9900        |
| 40      | 11300       | 6700        | –           | 6800        | 9100        |
| 48      | 10200       | 6800        | –           | 6800        | 9000        |
| 56      | 9800        | 6800        | –           | 6600        | 9000        |
| 71      | –           | 5600        | –           | 6600        | 8800        |
| 77      | –           | –           | –           | 6500        | 8800        |

Note—Doppler shift velocities of the absorption minima for several ions between 12 and 77 days. For all spectral profiles from SYN++ modeling, a constant uncertainty of 500 km s$^{-1}$ was estimated.

It has been noted for SN Ic bolometric light-curve fitting that best fits are obtained when we schematically consider the ejecta contributions to luminosity from two regions: a high-density inner region and a low-density outer region (Maeda et al. 2003; Valenti et al. 2008). We assume that the luminosities emitted by these two regions sum up to produce the overall luminosity when emission from the inner region is not absorbed by the outer counterpart. In the photospheric phase, the inner region is optically thick and its emerging luminosity is a small fraction of the total luminosity.

Figure 18. Bolometric luminosity with $BgVriJHK$ and additional UV contributions through SuperBOL blackbody extrapolations.

Model; Arnett 1982; Valenti et al. 2008; Chatzopoulos et al. 2012; Cano 2013) for the photospheric phase ($t < 45$ days). This model assumes a homologous expansion of uniform-density ejecta with no nickel mixing, a constant optical opacity ($\kappa_{opt}$), a small initial radius before explosion, and optically thick ejecta. We adopt the method of Valenti et al. (2008, see Eq. 1), where radioactive decay of both $^{56}$Ni and $^{56}$Co are assumed to be energy sources. As noted by Lyman et al. (2016), we account for an incorrect numerical factor, $3/5$ (see Eq. 2 of Valenti et al. 2008), instead of the correct fraction, $5/3$, which propagates into the expression for the timescale of the light curve ($\tau_m$ in Arnett 1982).

The best-fit bolometric light curve is presented in Figure 19. Assuming a constant opacity, $\kappa_{opt} = 0.07$ g cm$^{-2}$ (Cano 2013; Taddia et al. 2016), we obtain the following explosion parameters: nickel mass, $M_{Ni} = 0.118 \pm 0.007 M_\odot$; total ejecta mass, $M_{ej} = 2.76 \pm 0.44 M_\odot$; and explosion kinetic energy, $E_k = (0.73 \pm 0.23) \times 10^{51}$ erg. These are in reasonable agreement with those from our STELLA model fits (Table 2 and Section 3.1).

We revisit the degeneracy between ejecta mass and explosion kinetic energy as described in Section 3.1 (Figure 3) with additional constraints from spectroscopy. In the Arnett model, if one assumes a homogeneous density distribution of the ejecta, the measured photospheric velocity near peak luminosity ($v_{phot}$) is related to $M_{ej}$ and $E_k$ through the relation (Arnett 1982)

$$v_{phot} \approx \frac{5}{3} \sqrt{\frac{2E_k}{M_{ej}}}$$

Figure 19. Bolometric light-curve fit of photospheric phase ($t < 45$ days) with the Arnett model. The highest-likelihood model is presented as an orange curve and the corresponding 1σ posterior spread is displayed in gray.
Figure 20. Magnetar models alone can not reproduce the light curve of SN 2021krf and, in particular, the tail of the light curve at days 200–350.

From SYN++ models as discussed in Section 4.2, the measured photospheric velocity near peak luminosity (at day 21) is $7000 \pm 500$ km s$^{-1}$. In model CO-3.93 (Table 2), for the best-fit values of $M_{ej} = 2.49$ M$_{\odot}$ and $E_k = 0.5 \times 10^{51}$ erg, from the above equation we derive $v_{\text{phot}} = 7500$ km s$^{-1}$. On the other hand, for model CO-5.74 (Table 2), with corresponding best-fit parameters $M_{ej} = 4.08$ M$_{\odot}$ and $E_k = 1.05 \times 10^{51}$ erg, the derived velocity is $v_{\text{phot}} = 8500$ km s$^{-1}$. Thus, the combination of best-fit ejecta mass and explosion kinetic energy based on model CO-3.93 is in better agreement with the observed photospheric velocity near peak luminosity ($7000 \pm 500$ km s$^{-1}$) than when using CO-5.74. We note that a better fit using CO-3.93 compared to CO-5.74 is also obtained when simultaneously modeling the early- and late-time bolometric light curve in Section 4.4.2.

4.4.2. Modeling of Late-time Light Curves

The $^{56}$Ni radioactive decay powering the peak luminosity, along with its decay product $^{56}$Co at late times, cannot reproduce the late-time observed light curves (Figure 3). Arnett and STELLA models give consistent results in the photospheric phase (Table 2 and Section 4.4.1). Thus, we hereafter use a combination of STELLA models and an additional power source to fit the entire bolometric light curve including early- and late-time data. We consider heating of the ejecta by magnetic dipole radiation from a central neutron star (e.g., magnetar or millisecond pulsar) as an additional power source to fit the late-time excess. In our modeling, we hereafter refer to the magnetic neutron star as the central engine, which may be either a millisecond pulsar with relatively low magnetic fields ($B < 10^{14}$ G) or a magnetar with strong magnetic fields ($B \approx 10^{15}$ G).

Figure 21. (a) Best-fit model to the bolometric light curve combining radioactive decay ($M_{Ni} = 0.10$ M$_{\odot}$) along with an additional powering magnetar ($P_{\text{init}} = 12.62$ ms, $B_{\perp} = 1.451 \times 10^{15}$ G, $\chi^2_{\nu}=1.974$). (b) Distribution of the two-component light-curve model fits. The 90% and 99% confidence contours are consistent with $\chi^2_{\nu}=2.71$ (yellow) and 6.63 (green), respectively. A strong degeneracy between $B_{\perp}$ and $P_{\text{init}}$ is shown in the ranges of $10^{13}$–$5 \times 10^{13}$ G and 1–15 ms, respectively. (c) The $\chi^2_{\nu}$ distribution as a function of magnetic fields relative to the best-fit value ($B_0$). Magnetic fields are well constrained at $B_{\perp} < 5 \times 10^{15}$ G, but unconstrained in the lower bound.
This is because magnetar parameters at birth are not well constrained, thus making a wide parameter space of initial spin periods and magnetic fields possible depending on the properties of the progenitor system.

We considered two main scenarios for our models: (1) a magnetar without a nickel-decay contribution, and (2) a combination of a magnetar and nickel-decay ($M_{\text{Ni}} = 0.11, 0.10, \text{and } 0.05 M_{\odot}$). We employed Equations (2)–(7) of Nicholl et al. (2017) to calculate the bolometric luminosity added by magnetic dipole radiation heating from the neutron star. We constructed a two-dimensional parameter grid consisting of the initial spin period ($P_{\text{init}}$) and the component of magnetic field perpendicular to the spin axis ($B_{\perp}$), and fitted it to the bolometric light curve from Section 4.4.1. For the case with no nickel-decay contribution, we considered different onset dates of the central engine before the explosion date as a free parameter, $t_{\text{exp}}$. We fixed the optical opacity, $\kappa_{\text{opt}} = 0.1 \text{ g cm}^{-2}$, the opacity to high-energy photons, $\kappa_{\gamma} = 0.1 \text{ g cm}^{-2}$, and the mass of the central neutron star, $M_{\text{NS}} = 1.4 M_{\odot}$. For a magnetar as the sole powering source, we find that our models are not able to reproduce the entire bolometric light curve (the best-fit $\chi^{2}$ ≈ 20; Figure 20 and Table 7). In fact, the best-fit explosion date with this model is MJD 59318, which is 10 days before the last nondetection with ZTF (MJD 59328). Thus, a magnetar as the sole powering source is not a good model to explain the observations.

In the scenario of radioactive decay combined with an additional powering source, our model-fit results and grid parameters assuming two progenitor models (CO-3.93 and CO-5.74; Section 3.1) are shown in Table 7. We varied $B_{\perp}$ and $P_{\text{init}}$ over the parameter spaces $10^{11} - 5 \times 10^{15} \text{ G}$ and 0.5–500 ms, respectively. Fixing $M_{\text{Ni}}$ to the best-fit value ($M_{\text{Ni}} = 0.11 M_{\odot}$) found by our STELLA modeling (see Section 3.1 and Table 2), we find that the late-time excess of the bolometric light curve can be fitted by a pulsar with $B_{\perp} = 1.5 \times 10^{11} \text{ G}$ and an initial period $P_{\text{init}} = 1.5 \text{ ms}$. However, owing to degeneracies, large ranges of $B_{\perp}$ and $P_{\text{init}}$ ($B_{\perp} = 10^{11} - 5 \times 10^{13} \text{ G}$; $P_{\text{init}} = 1 - 15 \text{ ms}$) are allowed. We note that the gamma-ray trapping efficiency, which is parameterized with $\kappa_{\gamma}$ in our magnetar models, is uncertain at late times.

In these composite models the CO-3.93 progenitor models systematically provide better fits than the CO-5.74 model (see Table 7). A preference for CO-3.93 is also the case when constraining $M_{\text{ej}}$ and $E_k$ based on photospheric velocity at peak luminosity (see Section 4.4.1). For $M_{\text{Ni}} = 0.10 M_{\odot}$, the statistical improvement in the best-fit model is significant, particularly to fit the late-time excess ($\chi^2 \approx 1.9$; Table 7, Figure 21). Considering only CO-3.93, the best-fit parameters are $B_{\perp} = 1.45 \times 10^{13} \text{ G}$ and $P_{\text{init}} = 12.62 \text{ ms}$. Although this model fit is statistically good, it still allows for large ranges of parameter values (see Figure 21b, Figure 21c). However, our modeling clearly favors relatively low magnetic fields ($B_{\perp} < 5 \times 10^{13} \text{ G}$) to fit both the radioactive-powered peak and the late-time tail simultaneously.

As discussed above, our best-fit model is not unique and should only be considered as indicative. To get a better-constrained solution, a full parameter search is necessary, with an extensive model grid varying several different parameters simultaneously, including $E_k$, $M_{\text{Ni}}$, $B_{\perp}$, $P_{\text{init}}$, $\kappa_{\text{opt}}$, $\kappa_{\gamma}$, etc., which is beyond the scope of this paper. Our model fits with $M_{\text{Ni}} = 0.05 M_{\odot}$ are significantly worse than fits for higher nickel masses (Table 7), and are not able to reproduce the observed late-time fluxes.

Despite the uncertainties in model fitting, our results suggest that at early times ($t < 50 \text{ days}$ since the SN) the powering mechanism is dominated by radioactive decay, but at late times ($t > 200 \text{ days}$) the contribu-
tion from the central engine becomes significant. While the detailed properties of the powering sources of SN 2021krf are uncertain, we can confidently conclude that neither the $^{56}$Ni and $^{56}$Co radioactive decay alone (Figure 3) nor a magnetar as the sole power source (Figure 20) can adequately describe the observed light curves at both early and late times simultaneously. The central engine that is needed to account for the flat light curve at late times must have an initial period on the order of milliseconds and relatively low magnetic fields ($< 5 \times 10^{13}$ G). Because CSM interaction is unlikely at late times in SN 2021krf (see Section 4.1 and Figure 11), a SN-CSM interaction powering scenario to explain the late-time excess is not a likely possibility.

5. CONCLUSION

We have obtained NIR and optical observations of the Type Ic SN 2021krf in the galaxy 2MASX J12511712+0031138 (distance 65 Mpc) at the Gemini North Telescope, the NASA Infrared Telescope Facility, the Las Cumbres Observatory, the Southern Astrophysical Research Telescope, the Keck II Telescope, and the 3m Shane telescope at Lick Observatory. From this work, we present the following conclusions.

1. SN 2021krf has a relatively slow rising and declining time around the peak, and a broader light curve than other SNe Ic (like SN 2007gr, SN 2020oi, and SN 1994I), although less broad than SN 2011bu and iPTF15dtg, suggesting that it has a relatively low value of $E_k/M_{ej}$. The light curves of SN 2021krf become flatter at late times ($t > 200$ days) than other typical SNe Ic and $^{56}$Co radioactive decay, indicating the existence of an additional power source.

2. With calculations performed utilizing the one-dimensional multigroup radiation hydrodynamics code STELLA for SN 2021krf we discuss two degenerate solutions characterized by C-O star masses of 3.93 and 5.74 $M_\odot$, but with the same best-fit nickel mass of 0.11 $M_\odot$. The broad light curves indicate a low $E_k/M_{ej} \approx 0.2$. The C-O star masses of 3.93 and 5.74 $M_\odot$ correspond to $E_k$ of $0.5 \times 10^{51}$ and $1.05 \times 10^{51}$ erg, and $M_{ej}$ of 2.49 and 4.08 $M_\odot$, respectively. The models fit the observed light curve well at $t < 40$ days, but do not at $t > 70$ days. Our best-fit models as well as Arnett modeling (Figure 19) indicate that the photospheric phase ($t < 45$ days) of the light curves is well explained by radioactive decay alone.

3. Optical spectroscopic monitoring shows dominant P Cygni line profiles of Ca II and clear [O I] emission lines from day 71, progressively growing stronger until day 259, indicating the existence of significant amounts of O and Ca ejecta as expected from a stripped-envelope SN. Several Fe II lines appear $\sim 21$ days after the SN. Emission in the Na I doublet appears roughly at day 40 and increases in strength thereafter. NIR spectra show a strong Ca II triplet, O I, and S I absorption lines and weak lines of C I, Si I, and Mg I. No clear evidence of He I lines is observed.

4. Using the SYN++ code to model the optical spectra of SN 2021krf, we estimate a photospheric velocity of $10,000 \text{km s}^{-1}$ at day 12, a typical value of Type Ic SNe at early, pre-maximum phases. Significant temporal changes occurred between days 12 and 71, mainly from strong absorption due to O I and Ca II. The primary contributing lines to the spectra at day 71 are Ca II, O I, Fe II, Sc II, and Na I. Doppler shift velocities for individual ions are in the range 8000–12,000 km s$^{-1}$ at day 12 depending on the line elements, and they decrease to 6000–10,000 km s$^{-1}$ by day 71.

5. A rising continuum longward of 2 $\mu$m was observed at day 68, as well as evidence for overtone CO emission. Fits to the continuum (2.0–2.3 $\mu$m) using carbon dust and a grain size of 0.01, 0.1, and 1 $\mu$m yield dust masses of 2.4, 2.7, and $5 \times 10^{-5}$ $M_\odot$ and corresponding dust temperatures of 900, 880, and 1170 K, respectively. The estimated dust mass assuming MgSiO$_3$ dust is $2.8 \times 10^{-5}$ $M_\odot$ with a dust temperature of 1020 K.

6. To explain the rising continuum at day 68, we explored the possibilities that the dust is freshly formed in the ejecta, heated CSM dust, or an IR echo in the pre-existing CSM. Evolution of strong asymmetric intensities in the [O I] $\lambda\lambda$6300, 6364 line profile between days 48 and 71 in concurrence with the NIR excess at day 68 support formation of dust in the SN ejecta. The lack of H and He lines and the low extinction toward SN 2021krf suggest that there is no interaction taking place between the ejecta and a pre-existing circumstellar shell which could cause either emission from heated CSM dust or an IR echo from the circumstellar shell. The apparent lack of circumstellar shell in SN 2021krf, an SN Ic, is in contrast to typical Type II In SNe.

7. We modeled the heating of the ejecta by magnetic dipole radiation from a central neutron star (e.g., magnetar or millisecond pulsar) as an additional
power source to explain the late-time excess in the bolometric luminosity. Neither radioactive decay nor a magnetar as a sole power source can explain all of the observed features of the light curves. We reproduce the bolometric light curve with a combination of radioactive decay ($M_{Ni}=0.10M_\odot$) and an additional powering source in the form of a central engine with an initial period on the order of milliseconds (12.62 ms) and relatively low magnetic fields ($1.45 \times 10^{13}$ G); the latter explains the late-time flat light curve between days 200 and 350.

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