INFRARED ECHOES REVEAL THE SHOCK BREAKOUT OF THE CAS A SUPERNOVA

ELI DWER* AND RICHARD G. ARENDT

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ABSTRACT

Through the serendipitous discovery of infrared echoes around the Cas A supernova remnant, the Spitzer satellite has provided astronomers with a unique opportunity to study the properties of the echoing material and the history and nature of the outburst that generated these echoes. In retrospect, we find that the echoes are also clearly visible as infrared “hot spots” in IRAS images of the region. The spectra of the echoes are distinct from that of the dust in the general diffuse interstellar medium (ISM), revealing hot silicate grains that are either stochastically heated to temperatures in excess of ~150 K or radiating at an equilibrium temperature of this value. We show that the maximum luminosity that can be generated by the radioactive decay of $^{56}$Ni is not capable of producing such spectra, and could therefore not have given rise to the echoes. Instead, we find that the echoes must have been generated by an intense and short burst of EUV-UV radiation associated with the breakout of the shock through the surface of the exploding star. The inferred luminosity of the burst depends on the amount of attenuation in the intervening medium to the clouds, and we derive a burst luminosity of $\sim 1.5 \times 10^{11} L_\odot$ for an assumed H-column density of $1.5 \times 10^{19}$ cm$^{-2}$. The average H-column density of the IR-emitting region in the echoing clouds is about $5 \times 10^{17}$ cm$^{-2}$. Derivation of their density requires knowledge of the width of the echo that is sweeping through the ISM, which in turn is determined by the duration of the burst. A burst time of $\sim 1$ day gives a cloud density of $\sim 400$ cm$^{-3}$, typical of dense IR cirrus.

Subject headings: dust, extinction — infrared: ISM — ISM: individual (Cas A) — shock waves — supernovae: general — supernova remnants

1. INTRODUCTION

Short-lived luminous sources can produce echoes of their outburst in the ISM. These echoes can be manifested as line emission from the gas, or reflected and thermally reradiated light from the dust in the ISM. They can be used to probe the morphology of the interstellar medium (ISM) through which they are expanding and to reconstruct the historical record of the temporal behavior of the light source.

Visible light echoes have been detected around Nova Persei 1901 (Kapteyn 1902; Bode et al. 2004), V838 Mon (Bond et al. 2008), and SN 1987A (Crotts 1988). Fluorescent echoes arising from the equatorial ring around SN 1987A have been used to probe the early hours of the burst from the supernova (SN), the radius of the ring, and the distance to the Large Magellanic Cloud (LMC; Fransson & Lundqvist 1989; Panagia et al. 1991; Dwek & Felten 1992). The SuperMACHO project has discovered three additional sets of light echoes in the LMC that can be traced back to known supernova remnants (SNRs) and were used to derive ages of 610 and 410 yr for two of the SNRs (Rest et al. 2005).

One of the most unexpected discoveries made by Spitzer has been the serendipitous detection of infrared (IR) light echoes in the vicinity of the Cas A SNR. The possibility of detecting IR light echoes from ancient SNe in general, and Cas A in particular, has been considered by van den Bergh (1965) more than four decades ago. Cas A is the remnant of a supernova that exploded ~320 yr ago in the Perseus arm of the Galaxy, 3.5 kpc away. The echoes were first (and best) detected in 24 μm MIPS scans of Cas A (Fig. 1). Subsequent observations revealed that the echoes are also visible in all IRAC channels and ground-based $K$-band observations. The echoes vary on timescales of <6 months, and extend at least 1.5° from the SNR (Hines et al. 2004; Krause et al. 2005; Kim et al. 2008). More recently, Kim et al. (2008) have used the 24 μm maps of the echoes over a 3 yr interval to probe the structure of the ISM around Cas A, revealing its complex filamentary structure.

In this paper we combine early spectral observations with more recent data, which have revealed a wider extent of the echoes, to provide a detailed analysis of the nature of the radiative burst that gave rise to the echoes and the density of the interstellar clouds giving rise to the echoes.

We first present a brief review of the discovery of the echoes around Cas A, and derive the IR spectrum of select echoing clouds spanning a wide range of angular distances from the SNR (§ 2). We also provide a brief mathematical review of the geometry of an echo, and derive the distances of the echoing clouds from the center of the explosion. In § 3 we present the model input parameters: the burst delay time and its spectral characteristics, and the interstellar dust model used in the calculations. A stochastic heating model is used to calculate the thermal emission from the dust exposed to the burst of radiation, and in § 4 we describe the dependence of the calculated IR fluxes on the burst characteristics. The model fits are then used to derive the properties of the burst and the echoing clouds (§ 5). The results of our paper are briefly summarized in § 6.

2. THE INFRARED ECHOES AROUND CAS A

2.1. The Discovery of the Echoes

The initial MIPS 24 μm observations (a 0.2° x 0.3° scan map) of Cas A serendipitously revealed “chains of IR knots” extending up to ~12’ from the center of the SNR (Hines et al. 2004). The team followed up with ground-based $K$-band (2.2 μm) observations which revealed extremely high proper motions of the features. This motivated a second epoch of MIPS 24 μm observations that confirmed that much of the small-scale structure outside of the Cas A SNR was changing on timescales of several months.
months. A subset of the echoes seemed to represent a bipolar jet, nearly oriented in the plane of the sky, leading to the suggestion that at least these echoes may have been produced by a recent flaring of the Cas A neutron star around 1952 AD ± 2.5 yr (Krause et al. 2005), i.e., about 50 yr ago.

Subsequent MIPS 24 μm observations have been repeated at roughly 6 month intervals, and have been expanded to include at first a ~1° field around the SNR, and later a ~9° field. Examination of these data from the Spitzer archive reveal that echoes are not restricted to the bipolar structure originally detected. They are found at all position angles with respect to the SNR and extend at least 1.8° from the SNR (limited by the size of the map). The neutron starburst scenario was dismissed in passing by Kim et al. (2008). Here we will provide additional physical evidence against such scenario.

Follow-up observations of the echoes also included low- and high-resolution IRS observations of a bright echo in a filament located 0.8° from the center of the SNR. Additional low-resolution spectra were collected for outlying regions in the vicinity of the SNR. Two of the closest regions to the SNR, located within the northeast jet of ejecta and the southwest counterjet, have emission lines and the 22 μm silicate feature that are characteristic of ejecta material (Ennis et al. 2006; Rho et al. 2008). Spectra of other regions exhibited a flat continuum and coincide with highly variable features, and are therefore assumed to be representative echo spectra.3

The discovery of the echoes with Spitzer led us to examine whether the echoes could also be identified (in hindsight) in the map of the Cas A region that was obtained in 1983 with the Infrared Astronomical Satellite (IRAS). Figure 2 (left) shows a false-color image at 12, 25, and 60 μm of the reprocessed IRAS map of Cas A and its environment. The emission is dominated by cool interstellar dust grains, peaking at wavelengths of ~100–140 μm (red regions in the image). However, there are several regions with excess 25 μm emission (including Cas A itself) from hot dust, which thus appear green. Comparison to the 24 μm MIPS data (right panel), smoothed to IRAS resolution, clearly shows that the 25 μm excess features are echoes which have moved between 1983 and 2003. The fact that many echoes are in similar locations indicates that many of the clouds producing the echoes are structures that extend for at least 20 lt-yr along the line of sight (cf. Kim et al. 2008). IRAS and Spitzer have observed different portions of these large-scale structures.

2.2. The IR Spectrum of Select Echoes

For the purpose of this work we have concentrated on the analysis of six IR knots that were identified as echoes and have been the target of IRS observations. The selected echoes, listed in Table 1 and shown in Figure 1, sample a range of angular distances from the nominal center of the explosion. Also included in the table is a seventh 24 μm echo, without a spectrum, as a representative of the most distant echoing cloud. The SL+LL IRS spectra of the echoes were collected from the Spitzer archive.4 Because there are often several sources or extended emission within the slits, we have reprocessed the basic calibrated data (BCD) using the SSC tools irs_cleanmask and spice. The

3 Archival MIPS images were obtained from Spitzer programs PID = 718, 30571 (PI: G. Rieke), and PID = 231, 233, 20381 (PI: O. Krause).

4 Archival IRS spectra were obtained from Spitzer programs PID = 3310 (PI: L. Rudnick), and PID = 20381 (PI: O. Krause).
off-target subslit positions were used to subtract background emission for the corresponding on-target position. In a few cases where the off-target subslit position crossed the SNR, a clean subslit position from an alternate target was used. Both SL and LL data were processed, although in most cases the SL integration times were too short to detect the echoes, which are visible in all IRAC bands. Therefore the analysis presented here relies only on the LL spectra. Figure 3 presents the \( \sim 14\)–40 \( \mu \)m spectra of the echoes listed in Table 1.

All echoes within 1000\('\) of Cas A exhibit a steep rise in their spectrum between \( \sim 14\) and 20 \( \mu \)m, which is not seen in the IR spectra of dust in the diffuse ISM that is heated by the general interstellar radiation field (Draine & Li 2007). This spectral characteristic provides important clues to the nature of the emitting dust, strongly constraining the viability of different echo models. Echo 6 is brighter than the echoes closer to the SNR, and it is part of a large extended structure that can be seen in the older IRAS data. This region appears to contain a nonvariable emission component which would simply be the same cloud(s) illuminated by the diffuse interstellar radiation field. We have therefore subtracted a scaled ISM spectrum from the Echo 6 spectrum such that its 20–35 \( \mu \)m slope is within the range of the slopes of the other echo spectra. This nonvariable component accounted for \( 20\%–50\% \) of the 20–35 \( \mu \)m emission.

2.3. The Location of the Echoes

We assume that the echoes are the reradiated thermal emission from dust heated by the UV-visual output from the SN, located at point \( S \) (see Fig. 4). The emission from dust located at point \( C \) will be detected by an observer at point \( O \) with a delay time \( t \) given by

\[
ct = r + x - d,
\]

where \( r \) and \( x \) are, respectively, the distances of \( C \) from the source and the observer, and \( d = OS \) is the distance of the observer to the source. The locus of all points with equal delay time is an ellipsoid with the source and the observer at the focal points.

Using the law of cosines, \( r^2 = x^2 + d^2 - 2xd\cos(\alpha) \), we can express the distance \( r \) in terms of the delay time \( t \) and source distance \( d \),

\[
r = \frac{d(d + ct)[1 - \cos(\alpha)] + (ct)^2/2}{d[1 - \cos(\alpha)] + ct},
\]

Fig. 3.—Observed spectrum of the first six echoes listed in Table 1.

**TABLE 1**

| TARGET | R.A. | Decl. | \( \alpha^1 \) (arcsec) | \( r_{25}^2 \) (l-yr) | \( r_{35}^3 \) (l-yr) |
|--------|-----|-------|--------------------------|----------------------|----------------------|
| Echo 1 | 23 23 38.57 | +58 52 54.4 | 259 | 27.0 | 160.3 |
| Echo 2 | 23 22 50.58 | +58 47 30.6 | 300 | 27.6 | 160.4 |
| Echo 3 | 23 22 41.55 | +58 48 37.0 | 359 | 28.7 | 160.6 |
| Echo 4 | 23 22 50.98 | +58 41 49.4 | 508 | 32.5 | 161.2 |
| Echo 5 | 23 24 12.37 | +59 01 12.8 | 820 | 44.5 | 163.1 |
| Echo 6 | 23 21 39.96 | +59 34 26.9 | 2860 | 258 | 198 |
| Echo 7 | 23 26 38.62 | +57 01 19.4 | 6630 | 1172 | 359 |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

1 Angular distances were calculated from the optical expansion center located at (R.A.: decl.) = (23\(^\circ\)23\('\)27.77\('\) : +58\('\)48\('\)49.4\('\)) (Thorstensen et al. 2001).

2 Echo distances from the SN for a delay time of \( t = 50 \) yr.

3 Echo distances from the SN for a delay time of \( t = 320 \) yr.
where $\alpha$ is the angular distance of the echoing dust from the source.

Figure 5 shows three different depictions of the interrelations between the delay time and the angular and physical separations of the echoing clouds from the source assuming a source at the distance of Cas A, corresponding to $d = 3.4$ kpc (Reed et al. 1995). Figure 5 (top) shows the echo distance from the source, $r$, as a function of the delay time $t$ for the separation angles $\alpha$ corresponding to the echoes listed in Table 1. All distances are bound by the lower limit $ct/2$, which is the minimum distance corresponding to dust located at point $A$ immediately behind the source (see Fig. 4). The vertical lines represent the maximum delay time, corresponding to $t = 320$ yr, the age of Cas A, and a delay time of 50 yr. Figure 5 (middle) depicts the echo distance from the source as a function of angular separation. The vertical dashed lines correspond to the angular separations of the echoes listed in Table 1. The filled squares and open diamonds correspond to distances calculated for delay times of $ct = 320$ and 50 yr, respectively. Figure 5 (bottom) depicts the physical location of the echoes with respect to the source, as projected on a plane that includes the source, located at $(0,0)$, and the observer (off scale), located at $(d,0)$. The vertical line going through the origin represents the plane of the sky going through the source. The two ellipses shown in the figure are the loci of all points with equal delay times. The filled squares and open diamonds represent the echoes listed in Table 1, assuming delay times of 320 and 50 yr, respectively. With the largest separation angle from the source, Echo 7 is almost on the plane of the sky when $t = 320$ yr but at a large distance in front of the source when $t = 50$ yr.

The figures illustrate that when delay times are short, a given range of angular distances will correspond to a wide range of echo-source distances, whereas long delay times will translate into a significantly narrower range of echo-source distances for the same range of angular distances. When $t = 50$ yr, the range of distances, $r$, spanned by the echoes in Table 1 is between 27 and 1172 lt-yr. This range is narrowed to only 160 and 359 lt-yr when $t = 320$ yr (see Table 2).

### 3. Model Input Parameters

#### 3.1. The Echo Delay Time

The most obvious explanation for the echoes is that they were generated by the radiative energy released following the core collapse of the progenitor star of the Cas A SN, which occurred about 320 yr ago. Since Krause et al. (2005) suggested that a subset of the echoes were produced by a recent flaring of the neutron star that happened around 1950, we will also examine whether such an outburst could have produced the other echoes as well.

For each of the two scenarios ($t = 50$ or 320 yr) we determine the incident flux required to produce each echo spectrum. Since
the two scenarios require the echoing dust clouds to lie at different distances, these fluxes will translate into different burst luminosities. To check the viability of any physical scenario we require that all echoes are generated by a single burst with a well-defined intrinsic luminosity.

It is possible to construct scenarios involving multiple bursts from a neutron star over the past 320 yr. However, such scenarios have too many free parameters to be usefully constrained by the observations. Furthermore, the construction of such scenarios seems unnecessary given the consistent results that are ultimately obtained with the 320 yr old SN echo scenario.

3.2. The Burst Spectrum and Duration

Because neither the Cas A SN nor any subsequent outburst of the neutron star has been observed, we do not know the spectrum of the radiation that gave rise to the echoes. We will therefore explore three possible “burst” spectra: (1) an EUV spectrum characterized by a temperature of \( T_{\text{b}} = 5 \times 10^6 \) K; (2) a UV spectrum characterized by a temperature of \( T_{\text{b}} = 5 \times 10^4 \) K; and (3) an optical spectrum characterized by a temperature of \( T_{\text{b}} = 6000 \) K.

The radiative burst giving rise to the IR echo could be generated by the breakout of the SN shock wave through the stellar surface, in which case the burst is powered by the kinetic energy of the explosion. A flash of EUV-UV shock breakout radiation has been predicted by hydrodynamical simulations of SN explosions (Klein & Chevalier 1978; Falk 1978); however, because it lasts for only a few days, it has only recently been directly observed in a SN. Its existence was first indirectly inferred in SN 1987A from the detection of narrow UV and optical emission lines from the SN (Fransson et al. 1989; Sonneborn et al. 1997). The lines arise from an equatorial ring, located about 0.7 lt-yr from the SN and produced by mass loss from the progenitor star that was flash-ionized by the EUV burst. More recently, using the Swift X-ray Telescope, Soderberg et al. (2008) detected an X-ray burst from SN 2008D that they attributed to the shock breakout.

Alternatively, the IR echo could be powered by the energy released in the decay of radioactive elements that have formed in the SN explosion. In addition to the optical emission, a significant UV component has been observed with the Swift UV-optical Telescope in the light curves of all major types of SNe (Brown et al. 2008).

The IR spectrum of the echo depends on the spectral shape and intensity of the flux incident on the dust. The luminosities of the burst are free parameters that will be derived from model fits to the IR echoes. The duration of the burst is constrained by energy considerations and only affects the thickness and overall brightness of the expanding light echo. The burst duration is a necessary parameter in converting the derived column density into a volume density of the radiating dust.

3.3. Interstellar Dust Model

We used the BARE-GR-S model of Zubko et al. (2004) to characterize the echoing interstellar dust. The model consists of a population of bare silicate and graphite grains and polycyclic aromatic hydrocarbon (PAH) molecules (see Table 5 in their paper). In this model, the dust-to-gas mass ratio is 0.0062, and the abundance of its various dust constituents is consistent with solar abundances constraints. The size distribution of the different dust species are depicted in Figure 19 of their paper, and the parameters of their functional forms are listed in their Table 7.

4. Modeling the Echo Spectra

4.1. The IR Emission from Stochastically Heated Dust

The observed IR flux, \( F_{\nu}(\lambda) \), from an extended source of radiating dust is given by

\[
F_{\nu}(\lambda) = \left( \frac{\Omega}{\pi} \right) M_d \int \frac{d\alpha}{a^2} f(\alpha) \kappa(\nu, a) G_{\nu}(\lambda, a) \, da,
\]

where \( \Omega \) is the angular size of the dust cloud, \( M_d \) is the mass column density of the radiating dust, \( f(\alpha) \) is the grain size distribution normalized to unity over the \( \{a_1, a_2\} \) size interval, and \( \kappa(\nu, a) \) is the mass absorption coefficient of the dust. Implicit in equation (2) is a sum over dust composition. The term \( \kappa(\nu, a) G_{\nu}(\lambda, a) \) in the equation is the spectral response of the dust to an incident radiation field, with \( G_{\nu} \) given by an integral over dust temperatures \( T_d \),

\[
G_{\nu}(\lambda, a) \equiv \int_{T_d} P(T_d) \pi B_{\nu}(T_d, \lambda) \, dT_d,
\]

where \( P(T_d) \) (K\(^{-1}\)) is the temperature probability distribution of the stochastically heated dust, and \( B_{\nu}(T_d, \lambda) \) is the Planck function. For dust radiating at the equilibrium temperature \( T^{eq}_d \), \( P(T_d) \) collapses to the delta function \( \delta(T^{eq}_d - T_d) \), and \( G_{\nu}(\lambda, a) = \pi B_{\nu}(T^{eq}_d, a) \).

4.2. Echo Spectra For Different Burst Models

To model the IR emission from the echoing clouds we will expose a population of interstellar dust to a burst of radiation

| Burst Model Parameter | 1     | 2     | 3     | 4     | 5     | 6     |
|-----------------------|-------|-------|-------|-------|-------|-------|
| \( \xi_F \)           | 0.6   | 0.6   | 0.8   | 0.2   | 0.3   | 0.6   |
| \( L_b \)             | 0.60  | 0.60  | 0.81  | 0.20  | 0.31  | 0.92  |
| \( N_H \)             | 2.7   | 1.6   | 1.9   | 1.3   | 3.0   | 9.7   |
| \( \chi^2 \)          | 2.20  | 2.46  | 4.62  | 1.81  | 1.72  | 1.31  |
| \( \xi_F \)           | 0.2   | 0.2   | 0.2   | 0.04  | 0.08  | 0.1   |
| \( L_b \)             | 0.20  | 0.20  | 0.20  | 0.041 | 0.083 | 0.15  |
| \( N_H \)             | 4.7   | 2.8   | 4.2   | 4.4   | 7.1   | 32.0  |
| \( \chi^2 \)          | 1.67  | 1.66  | 3.98  | 1.00  | 1.03  | 1.13  |
| \( \xi_F \)           | 0.2   | 0.2   | 0.4   | 0.06  | 0.1   | 0.2   |
| \( L_b \)             | 0.20  | 0.20  | 0.40  | 0.06  | 0.10  | 0.31  |
| \( N_H \)             | 7.7   | 4.6   | 3.5   | 4.9   | 9.5   | 26.9  |
| \( \chi^2 \)          | 2.40  | 2.94  | 3.21  | 1.05  | 1.40  | 1.00  |
| \( \xi_F \)           | 2.0   | 2.0   | 2.0   | 0.4   | 0.8   | 1.0   |
| \( L_b \)             | 2.0   | 2.0   | 2.0   | 0.41  | 0.83  | 1.53  |
| \( N_H \)             | 3.5   | 2.1   | 3.1   | 3.2   | 5.2   | 23.8  |
| \( \chi^2 \)          | 1.93  | 1.74  | 3.16  | 1.03  | 1.00  | 1.10  |
| \( \xi_F \)           | 0.1   | 0.1   | 0.2   | 0.02  | 0.06  | 0.1   |
| \( L_b \)             | 0.10  | 0.10  | 0.20  | 0.020 | 0.062 | 0.15  |
| \( N_H \)             | 5.8   | 3.5   | 2.8   | 5.4   | 5.9   | 20.6  |
| \( \chi^2 \)          | 1.00  | 1.52  | 1.00  | 1.64  | 1.10  | 1.09  |
| \( \xi_F \)           | 0.2   | 0.2   | 0.2   | 0.04  | 0.08  | 0.1   |
| \( L_b \)             | 0.20  | 0.20  | 0.20  | 0.041 | 0.083 | 0.15  |
| \( N_H \)             | 3.6   | 2.2   | 3.2   | 3.2   | 5.3   | 24.0  |
| \( \chi^2 \)          | 1.14  | 1.00  | 1.45  | 1.28  | 1.07  | 1.29  |
| \( \xi_F \)           | 0.4   | 0.2   | 0.4   | 0.06  | 0.1   | 0.2   |
| \( L_b \)             | 0.40  | 0.20  | 0.40  | 0.061 | 0.10  | 0.31  |
| \( N_H \)             | 3.0   | 3.4   | 2.7   | 3.5   | 6.9   | 20.0  |
| \( \chi^2 \)          | 1.50  | 2.23  | 1.17  | 1.41  | 1.61  | 1.22  |
emanating from the SN. The burst spectrum will be characterized by a blackbody at a fixed temperature $T_b$. A significant fraction of its soft X-rays and EUV photons will be absorbed in the intervening medium between the SN and the clouds. The optical depth, $\tau(C_28) = C_28 N_{\text{H}}$, will be parameterized by the intervening ISM column density, $N_{\text{H}}$. The flux incident on the dust grains is then given by

$$F^b_{\nu}(\lambda) = \xi F_0 \left[ \frac{\pi B_{\nu}(T_b, \lambda)}{\sigma T_b^4} \right] e^{-\tau(\lambda)},$$

(4)

where $F_0$ is a fixed flux, calculated for a nominal luminosity $L_0 = 1 \times 10^{12} L_\odot$ and a nominal distance of $r_0 = 160$ lt-yr between the radiating dust and the source, and $\xi$ is a flux scaling parameter determined by the fit to the observed spectrum of the IR echo. Numerically, $F_0$ is given by

$$F_0 = \frac{L_0}{4\pi r_0^2} = 1.33 \times 10^4 \text{ erg s}^{-1} \text{ cm}^{-2}.$$  

(5)

Since the H-column density to the echoing clouds is unknown, we will calculate the burst’s attenuation for three different H-column densities given by $N_{\text{H}} = 1.5 \times 10^{18}, 1.5 \times 10^{19},$ and $1.5 \times 10^{20}$ cm$^{-2}$. For a typical echo distance of 160 lt-yr, these column densities correspond to average ISM densities of $n_{\text{H}} = 0.01$, 0.1, and 1.0 cm$^{-3}$, respectively.

Our burst model calculations were performed for seven different burst spectra characterized by different burst temperatures and intervening H-column densities. Burst models are designated by their spectra, EUV for $T_b = 5 \times 10^5$ K, UV for $T_b = 5 \times 10^4$ K, and OPT for $T_b = 6000$ K, and by a suffix of 18, 19, or 20, corresponding to the assumed SN-echo column density.
For example, model EUV19 corresponds to a burst with a temperature of $5 \times 10^5$ K and a column density of $1.5 \times 10^{19}$ cm$^{-2}$ for the echoing clouds. Model UV20 corresponds to a burst with a temperature of $5 \times 10^4$ K and an ISM column density of $1.5 \times 10^{20}$ cm$^{-2}$. We neglected any attenuation for the OPT burst. This model lacks any significant ionizing radiation, and therefore the extinction was negligible even for the largest column density.

We calculated echo spectra for each burst spectrum for a grid of fluxes, characterized by different values of $\xi$ ranging from $10^{-3}$ to 10. For example, we calculated 16 IR spectra for burst model EUV18 by varying $\xi$ from 0.001 to 1.0 with 14 intermediate values. The only free model parameter is the normalization factor, which is equal to the dust mass column density, $M_d$, of the model spectrum that produced the lowest value of $\chi^2$.

Figure 6 compares the fluxes from the different burst scenarios outlined above as they are incident on an echoing cloud at a distance of 160 lt-yr from the SN. For illustrative purposes, the fluxes from the EUV and UV bursts were calculated for values of $\xi$ ranging from 0.001 to 1.0, and the flux from the optical burst was calculated for $\xi = 0.01$, reflecting its expected lower luminosity. For sake of comparison, the figure also includes the flux of the general interstellar radiation field (ISRF; Mathis et al. 1983).

Figures 7, 8, and 9 depict the results for the OPT, the EUV, and the UV bursts, respectively. The top panels in the figures show the calculated IR spectra of dust that is exposed to a range of illuminating fluxes, characterized by different values of $\xi$. To illustrate the dependence of the spectral signature of the dust on the flux and spectral shape of the incident radiation we normalized all fluxes to unity at $\lambda = 20$ $\mu$m. The middle panels depict the best fits to the echo spectra by the incident fluxes. Different echoes required exposure to different fluxes to fit their IR spectra. The bottom panels of the figures show the contributions of the different dust components to the total flux from Echo 3.

The figures show that the radiation from the optical burst cannot reproduce the observed characteristic rise in the echo spectra from 14 to 20 $\mu$m. In contrast, both the EUV and UV models reproduce the echo spectra fairly well, independent of the density of the intervening medium.

The decomposition of the fits to Echo 3 into the various dust components illustrates that the rapid rise in the echo spectra between ~14 and 20 $\mu$m is caused by the 18 $\mu$m silicate feature. Two conditions have to be met to produce the observed rise in the echoes' spectra: (1) the silicate grains have to be heated to temperatures in excess of ~150 K; and (2) the silicate emission has to dominate the emission from graphite grains which have a smooth spectrum over the ~10–40 $\mu$m wavelength interval. The echoes generated by the optical burst fail to meet both conditions. Silicate grains have a low opacity to optical photons.
and therefore remain at relatively low temperatures. The top panel of Figure 10 shows that the equilibrium silicate temperature is only about 83 K for the OPT burst. Stochastic heating is limited to the smallest grains with sizes $P < 70 \mu m$. In contrast, graphite grains have a much larger opacity at visible wavelengths and attain much higher equilibrium temperatures of $\sim 175 K$. Consequently, the IR echo spectrum produced by the optical burst is dominated by graphite emission.

The EUV and UV bursts meet both requirements for producing the rise in the echo spectra. As shown in Figure 10, they both possess sufficiently hard photons to raise the equilibrium silicate temperature to $\sim 150 K$. Compared to the optical burst, a larger fraction of the small grains are fluctuating to temperatures beyond $\sim 100 K$. Furthermore, the opacity of silicate grains rises dramatically in the EUV, and becomes comparable to that of the graphite grains. Consequently, as illustrated in the bottom row of Figures 8 and 9, the total IR spectrum is dominated by silicate emission.

4.3. A Fit to the Average Echo Spectrum

It is of interest to examine to what extent our model fits to the $\sim 14$–$40 \mu m$ echo spectra. The best fit to the spectrum of echo 3 is shown in Figure 11. The bottom plot shows the decomposition of the best-fitting IR spectrum of Echo 3 into its emission components from silicate and graphite grains and PAHs. A detailed discussion of the figure is in the text.

The figure shows that if the echoes are only observed in the broad IRAC and MIPS $24 \mu m$ bands, their colors are very similar to those of interstellar cirrus dust. Consequently, the true temperature of the echoes is totally lost with this limited photometric data. In contrast, the $IRAS 25 \mu m$ to $60 \mu m$ color ratio was able to distinguish between the echoing clouds and the interstellar cirrus (Zubko et al. 2004). The temperature of the echoing dust is much higher than that of the dust in cirrus clouds, requiring an incident flux that is significantly harder than the general ISRF.
The excess 2.2 μm emission is caused by reflection, and may therefore sample a totally different portion of the SN light curve, powered by the radioactivities in the ejecta. The intensity of the reflected echo could therefore provide valuable information of the Cas A progenitor. The column density of the scattering dust could therefore be significantly higher than that of the thermally emitting dust, providing a geometry-dependent observational test of this hypothesis.

5. MODEL RESULTS

5.1. Burst Scenario and Derived Burst Properties

The incident flux that provides the best fit to a given echo spectra can be converted to burst luminosity by

\[ L_b = \left( \frac{r}{r_0} \right)^2 \xi_F \xi L_0, \]

where \( r \) is the actual distance of the particular echo from the SN, \( L_0 = 1 \times 10^{12} L_\odot \), and \( \xi_F \) is the value of \( \xi \) that produced the best-fitting incident flux.

Each echo requires a particular incident flux to produce its IR spectrum. Given this flux, the value of \( \xi_F \) depends on the assumed column density of the intervening ISM (see eq. [4]). A higher column density will require larger values of \( \xi_F \), corresponding to larger burst luminosities.

Figures 12 and 13 depict the burst luminosities required to produce the echo spectra for the different burst models and delay time scenarios. We assume that all echoes were produced by a single burst. A viable echo scenario should therefore give the same burst luminosity for all echoes. The results show that a scenario with a 50 yr delay time produces a large spread in burst luminosities, compared to the 320 yr delay scenario. The figures show that the dispersion in the derived burst luminosities for the latter scenario is only about 50% of the mean value (see also Table 3), compared to a factor of 2 in the former. This is a direct consequence of the fact that the echo spectra are generally very similar, thus requiring exposure to the same incident flux of radiation. Narrowing the range of burst luminosities for the 50 yr delay model will require more distant echoes to have systematically lower column density, a nonphysical and contrived solution.
to this problem. We therefore support the conclusion of Kim et al. (2008) that the echoes were not generated by a hypothetical burst from the neutron star occurring about 50 yr ago. In principle, all echoes could have been produced by repeated bursts occurring over a period of 320 yr. However, a more likely scenario is that

Table 2 lists the model fits for each of the echoes assuming a 320 yr delay time. For each model we present the incident flux required to produce the best fit to the echo spectrum as characterized by the value of $\chi^2$ of the fit. For each echo, the value of $\chi^2$ was normalized to unity for the best-fitting model. From the values of the $\chi^2$ of the fit, we see that the OPT burst provides a significantly worse fit to the echo spectra than the EUV and UV bursts. The EUV and UV bursts are generally of similar quality, although for echoes 1, 2, and 3, UV models

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are distinctly better. The models with a lower H-column density usually provided slightly better fits than the models with \( N_{\text{HI}} = 1.5 \times 10^{20} \text{ cm}^{-2} \).

The lack of any evidence for H-recombination lines from the gas around Cas A (Krause et al. 2005) suggests that the burst ran out of ionizing photons before it reached the echoing clouds. Inspection of Figure 6 shows that these conditions are easily met when the intervening H-column density is sufficiently high, with \( N_{\text{HI}} \geq 10^{20} \text{ cm}^{-2} \).

Table 3 lists the burst luminosity averaged over all echoes for each burst model. It clearly shows the correlation between the derived burst luminosity and the column density of the intervening ISM. Larger column densities require higher burst luminosities to produce the same flux needed to produce the observed echo spectrum. Excluding model results for the highest column density, we conclude that the average EUV-UV burst luminosity is \( L_b = 1.5 \times 10^{51} \text{ L}_\odot \).

5.2. The EUV-UV Burst Must be Powered by Shock Energy

In principle, the EUV-UV luminosity could be either powered by the explosion energy or by the radioactive decay energy in the ejecta. A simple analysis, based on the best estimate of the properties of the Cas A progenitor (Young et al. 2006), firmly rules out the latter possibility. Based on explosion calculations, ejecta velocity and mass constraints, and \(^{44}\text{Ti} \) yields, Young et al. (2006) estimate the mass of \(^{56}\text{Ni} \) to be between 0.06 and 0.2 \( M_\odot \).

Taking the average decay energy to be 1.73 MeV and a decay lifetime of 8.8 days, the maximum luminosity that can be powered by the decay of \(^{44}\text{Ti} \) is between 1.2 and \( 4.1 \times 10^7 \text{ L}_\odot \). This luminosity is about 2 orders of magnitude smaller than that required to produce the IR echoes.

The luminosities required to produce the echoes are easily obtained by tapping into the kinetic energy of the explosion. Taking an average explosion energy of \( 2 \times 10^{51} \text{ erg} \) (Young et al. 2006) suggests that this energy must be released during a period of 40 days to produce an average luminosity of \( 1.5 \times 10^{51} \text{ L}_\odot \). Several hydrodynamic models for the explosion of SN 1987A were constructed to fit the earliest UV and optical light curve (Woosley 1988; Ensmann & Burrows 1992; Blinnikov et al. 2000). The models of Blinnikov et al. (2000) show that the burst had a peak blackbody temperature of \( \sim 10^6 \text{ K} \), cooling on a timescale of days to a blackbody temperature of \( \sim 6000 \text{ K} \), the H-recombination temperature in the expanding photosphere. Burst durations are therefore typically \( \lesssim \) days. Taking a burst decay time of 1 day suggests that only 2.5% of the kinetic energy of the explosion needs to be thermalized to produce the required EUV-UV luminosity. These simple arguments conclusively show that the echoes have revealed the breakout of the SN shock through the stellar surface. The combined constraints on the energy of the explosion, the required burst luminosity, and hardness of its spectrum can provide useful constraints for modeling the structure of the progenitor of Cas A (Matzner & McKee 1999).

5.3. Derived Cloud Properties

From the fits of the calculated IR spectra to the observations we can derive the column density, \( M_d \) of the emitting dust. We take \( \Omega \) to be the width of the IRS LL slit squared, \( \Omega = (10.62) \). The corresponding H-column density is given by \( N_{\text{HI}} = M_d / (m_{\text{HI}} Z_{\text{HI}}) \), where \( Z_{\text{HI}} = 0.0087 \) is the dust-to-H mass ratio of the BARESG-S Zubko et al. (2004) interstellar dust model, and \( m_{\text{HI}} \) is the mass of the H atom. The column densities derived for each echo and burst model are listed in Table 2. Echo 6 is the brightest, and consequently has the highest H-column density. Table 4 lists the column density of each echo, averaged over all EUV and UV burst models. The average column density for Echoes 1–5 is about \( 5 \times 10^{17} \text{ cm}^{-2} \), and higher by a factor of ~4 for Echo 6.

All echoes within 50° of Cas A are located behind the SN. The IR emission arises from a narrow region of thickness \( c \Delta t_b \), where \( \Delta t_b \) is the burst duration along the observer’s line of sight that is illuminated by the burst of radiation. The width of the radiation front is determined by the burst duration \( \Delta t_b \). The hydrogen number density, \( n_{\text{HI}} \), of the echoing cloud can be derived from the dust mass column density, \( M_d \), by

\[
N_{\text{HI}} = \frac{(M_d)}{(m_{\text{HI}} Z_{\text{HI}})} (c \Delta t_b)^{-1} \approx 200 \frac{n_{\text{HI}}}{\Delta t_b (d)} \text{ cm}^{-3},
\]

where the numerical value was derived for a nominal echo column density of \( N_{\text{HI}} = 5 \times 10^{17} \text{ cm}^{-2} \).

The burst duration should be taken as the length of time during which the burst spectrum is dominated by EUV-UV emission. From the models of Blinnikov et al. (2000) we take this time to be about 1 day, giving an average cloud density of \( n_{\text{HI}} \approx 385 \text{ cm}^{-3} \). This is a plausible density for the echoing clouds, corresponding to those of typical cirrus clouds (Wolfire et al. 2003). Cas A lies on the far side of the Perseus arm (e.g., Bieging et al. 1991), so there are relatively few (if any) denser molecular clouds behind the remnant (Ungerechts et al. 2000) to reflect the radiative burst from the SN.

6. SUMMARY

The Spitzer satellite discovered a series of IR echoes around Cas A that are caused by the delayed arrival of thermal emission from dust heated by the radiative output from the SN. Echo
spectra are distinct from the IR emission from the diffuse ISM, exhibiting a sharp rise at wavelengths from \(~14\) to \(20\) \(\mu\)m. In hindsight, the echoes can also be found in the IRAS images from 1983.

We assume that the echoes are generated by thermal emission from interstellar dust heated by a single burst of radiation released after the SN event. We calculated the fluxes incident on the dust required to generate the observed echo spectra for different bursts characterized by blackbody spectra with temperatures of \(5 \times 10^5\) (EUV burst), \(5 \times 10^4\) (UV burst), and 6000 K (optical burst).

Our models show that the rise in the echo spectra is due to the 18 \(\mu\)m silicate feature. The silicate grains radiate mostly at the equilibrium temperature of \(\sim 120\) K and dominate the echo spectra. The optical burst is incapable of heating the silicates to a sufficiently high temperature to reproduce the spectral characteristics of the echoes, and is therefore ruled out as the source of the echoes.

The echoes are instead generated by the intense EUV-UV burst of radiation generated by the shock breakout. We show that the echo spectra can be reproduced by bursts with a wide range of temperatures from \(\sim 5 \times 10^4\) to \(\sim 5 \times 10^5\) K. The burst luminosity required to generate the echoes depends on the assumed H-column density between the SN and the echoing cloud. We find the average burst luminosity to be \(\sim 1.5 \times 10^{11} \, L_{\odot}\) for an average intervening H-column density of \(\sim 1.5 \times 10^{19} \, \text{cm}^{-2}\).

The average H-column density of the echoing clouds is \(\sim 5 \times 10^{17} \, \text{cm}^{-2}\), which for a burst duration time of \(\sim 1\) day gives an average cloud density of \(\sim 400 \, \text{cm}^{-3}\). This density is typical of dense cirrus clouds, and it is consistent with the location of Cas A behind the Perseus arm and the paucity of dense molecular material behind the remnant.

The luminosity required to produce the echoes cannot be generated by the radioactive decay of the 0.06--0.2 \(M_\odot\) of \(^{56}\)Ni that has formed in the explosion, and must therefore reflect the fraction of the kinetic energy of the explosion that was converted to EUV-UV radiation as the SN shock broke out through the stellar surface. The Cas A echoes represent the first indirect “view” of a shock breakout via the thermal dust emission from echoing clouds.

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