moving from work that has cataloged the patterns of \( \text{fMRI} \) activity associated with specific categories of words and pictures to instead building computational models that predict the \( \text{fMRI} \) activity for arbitrary words (including thousands of words for which \( \text{fMRI} \) data are not yet available). This is a natural progression as the field moves from pretheoretical cataloging of data toward development of computational models and the beginnings of a theory of neural representations. Our computational models can be viewed as encoding a restricted form of predictive theory, one that answers such questions as “What is the predicted \( \text{fMRI} \) neural activity encoding word \( w \)” and “What is the basis set of semantic features and corresponding components of neural activation that explain the neural activations encoding meanings of concrete nouns?” Although we remain far from a causal theory explaining how the brain synthesizes these representations from its sensory inputs, answers even to these questions promise to shed light on some of the key regularities underlying neural representations of meaning.

References and Notes

The Cassiopeia A Supernova Was of Type IIb

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Cassiopeia A is the youngest supernova remnant known in the Milky Way and a unique laboratory for supernova physics. We present an optical spectrum of the Cassiopeia A supernova near maximum brightness, obtained from observations of a scattered light echo more than three centuries after the direct light of the explosion swept past Earth. The spectrum shows that Cassiopeia A was a type IIb supernova and originated from the collapse of the helium core of a red supergiant that had lost most of its hydrogen envelope before exploding. Our findings conclude a long-standing debate on the Cassiopeia A progenitor and provides new insight into supernova physics by linking the properties of the explosion to the wealth of knowledge about its remnant.

The supernova remnant Cassiopeia A is one of the most-studied objects in the sky, with observations from the longest radio waves to gamma rays. The remnant expansion rate indicates that the core of its progenitor star collapsed around the year 1681 ± 19, as viewed from Earth (J). Because of its youth and proximity of 3.4 ± 0.3 kpc (2), Cass A provides a unique opportunity to probe the death of a massive star and to test theoretical models of core-collapse supernovae. However, such tests are compromised because the Cass A supernova showed at most a faint optical display on Earth at the time of explosion. The lack of a definitive sighting means that there is almost no direct information about the type of the explosion, and the true nature of its progenitor star has been a puzzle since the discovery of the remnant (3).

The discovery of light echoes due both to scattering and to absorption and re-emission of the outgoing supernova flash (4–5) by the interstellar dust near the remnant raised the possibility of conducting a postmortem study of the last historic Galactic supernova by observing its scattered light. Similarly, the determination of a supernova spectral type long after its explosion using light echoes was recently demonstrated for an extragalactic supernova (6).

We have monitored infrared echoes around Cas A at a wavelength of 24 μm with use of the multiband imaging photometer (MIPS) instrument aboard the Spitzer Space Telescope (4). The results confirm that they arise from the flash emitted in the initial explosion of Cas A (5). An image taken on 20 August 2007 revealed a bright (flux density \( F_{24\mu m} = 0.36 \pm 0.04 \) Jy, \( 1 \) Jy = \( 10^{-26} \) W m\(^{-2}\) Hz\(^{-1}\)) and mainly unresolved echo feature located 80 arc min northwest of Cas A (position angle 311° east of north). It had not been detected (\( F_{24\mu m} \leq 2 \) mJy; 5-σ) on two previous images of this region obtained on 2 October 2006 and 23 January 2007 (Fig. 1).

An image obtained on 7 January 2008 shows that the peak of the echo has dropped in surface brightness by a factor of 18 and shifted toward the west. Transient optical emission associated with the infrared echo was detected in an R-band image obtained at a wavelength of 6500 Å at the Calar Alto 2.2-m telescope on 6 October 2007.

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with a peak surface brightness $R = 23.4 \pm 0.2$ mag arc sec$^{-2}$. No optical emission feature down to surface brightness limit $R = 25.1$ mag arc sec$^{-2}$ (3-$\sigma$) was detected toward this position in a previous $R$-band image obtained at the Steward Observatory 90-inch telescope on 18 September 2006.

We have acquired a deep $R$-band image of the echo with the faint object camera and spectrograph (FOCAS) instrument at the Subaru telescope on 9 October 2007 (Fig. 2). The morphology of the optical emission in this image closely matches the mid-infrared one observed 50 days earlier, with the echo resolved into compact emission knots of about 2 arc sec diameter in the $R$-band image. A long-slit spectrum covering the northern one of these compact knots (Fig. 2B) was obtained with FOCAS on the same night, covering the wavelength range from 4760 to 9890 Å with a spectral resolution of 24 Å.

This echo spectrum unambiguously shows light of a supernova origin (Fig. 3). Broad emission lines with P-Cygni absorption components from neutral and singly ionized elements are detected, all of which are commonly observed in core-collapse supernovae. A prominent feature of the Cas A supernova spectrum is an H$\alpha$ emission line with a full width at half maximum (FWHM) of 17,000 km s$^{-1}$ and a blue-shifted absorption minimum at $-11,000$ km s$^{-1}$. Other strong lines are Na I D, the Ca II infrared triplet, and permitted emission lines of neutral oxygen at 7774 and 9264 Å. In addition, lines of He I 7065 Å and likely also He I 5876 Å (blended with Na I D) and He I 7821 Å (blended with [Ca II] 7291, 7324 Å) are detected.

Whereas the presence of the hydrogen line characterizes Cas A as a type II supernova (SN), the additional appearance of weak helium lines and singly ionized elements is characteristic of the rare class of type Ib supernovae (SNe). They originate from the core collapse of massive stars that have lost most of their hydrogen envelopes before exploding and consist of a nearly bare helium core at the time of collapse. SNe Ib initially show a type II spectrum dominated by their hydrogen-poor envelope and gradually transform into a SN Ib spectrum from the inner helium core (7–9). A type Ib for the Cas A supernova is supported by comparing its spectrum with that of the prototypical type SN Ib, 1993J (10) (Fig. 3), the collapse of a red supergiant (II) with a main sequence mass of 13 to 20 $M_\odot$ (12, 13) in the nearby galaxy M81. The spectra are remarkably similar in terms of the presence of important spectral features and their strengths. The echo spectrum visible on Earth represents supernova light over an interval of time around maximum brightness because of the spatial extent of the interstellar cloud; therefore, the comparison spectrum was derived as the time-average of brightness-weighted spectra of SN 1993J obtained during days 1 to 83 after collapse (10, 14), consistent with the geometrical constraints of the echo (Fig. S1).

The identity of the Cas A progenitor has been the subject of tremendous debate (15). A type II or Ib has been suggested for the Cas A supernova (16, 17) on the basis of detection of a few remnant ejecta knots containing some hydrogen at space velocities between 9000 and 10,300 km s$^{-1}$ (17, 18). The flat-top shape of H$\alpha$ emission in our Cas A spectrum is consistent with a thin hydrogen-rich shell above the photosphere and expanding at about 10,000 km s$^{-1}$. In contrast, the overall lack of hydrogen emission in most knots and the nitrogen enrichment in the remnant were widely interpreted as signatures of the collapse of a Wolf-Rayet star in a type Ib supernova (18). The SN Ib 2005bf was likely produced by a nitrogen-rich Wolf-Rayet star and has been proposed for a possible template for the Cas A supernova (19). However, the spectrum of SN 2005bf does not provide a good match to our spectrum of the Cas A supernova.

Further evidence for a red supergiant progenitor comes from the comparison of SN 1993J with Cas A: Radio and x-ray observations of SN1993J imply a mass-loss rate of $4 \times 10^{-5} M_\odot$ year$^{-1}$ and a wind velocity of 10 km s$^{-1}$ (20), close to an estimate of $2 \times 10^{-5} M_\odot$ year$^{-1}$ and wind velocity of 10 km s$^{-1}$ consistent with the hydrodynamical state of the Cas A remnant (16). The presence of broad absorption components in the Cas A spectrum and the absence of prominent unresolved lines differ from typical spectra of SNe IIn whose ejecta are directly interacting with dense circumstellar gas. In the case of Cas A, the dense circumstellar wind may therefore not have extended directly to the surface, and Cas A might have exploded into a bubble created by a temporary phase of enhanced wind velocity. In addition, evidence for CNO processing in the envelope of a red supergiant has been found in the remnants of both SN 1993J (21) and Cas A (22). A helium core mass of 3 to 6 $M_\odot$ inferred for SN 1993J (12, 13) matches the total mass at core collapse of Cas A based on the observational constraints for its remnant (15).

The optical brightness of a SN Ib results from the production of a substantial amount of $^{56}$Ni, which for the SN 1993J supernova has been determined to be between 0.07 and 0.15 $M_\odot$ (12, 13, 23). Models of nucleosynthesis predict an associated amount of $7 \times 10^{-4}$ to $1.7 \times 10^{-3} M_\odot$.

Fig. 1. Infrared images of the echo region. (A to D) MIPS 24-μm images of the same area of 2.5 arc min by 5 arc min with the corresponding observing epoch labeled on each panel. The bright infrared echo is visible at the center of (C). Other infrared echoes ~60 arc sec north of this feature are indicated by strong emission in (C) and has been proposed for a possible template for the Cas A supernova (19). However, the spectrum of SN 2005bf does not provide a good match to our spectrum of the Cas A supernova.

Fig. 2. Optical images of the echo region. (A to C) show $R$-band images of the same area of 33 arc sec by 33 arc sec with the corresponding observing epoch labeled on each panel. The bright infrared echo is visible at the center of (C). Other infrared echoes ~60 arc sec north of this feature are indicated by strong emission in (C) and has been proposed for a possible template for the Cas A supernova (19). However, the spectrum of SN 2005bf does not provide a good match to our spectrum of the Cas A supernova.
44Ti produced for a stellar mass of 15 to 20 M\(_{\odot}\) (23). A 44Ti mass of 1.6\(10^{-3}\) × 10\(^{-3}\) M\(_{\odot}\) has been measured in the Cas A remnant (24). This is consistent with the Cas A supernova being an optically bright supernova such as SN 1993J.

Because the density and composition of the interstellar cloud giving rise to the echo is relatively unconstrained, it is difficult to accurately determine the peak brightness and light curve of Cas A from the scattered light. The circumstances regulating the infrared emission are simpler, and because the dust cooling time in the infrared echo is short (5) the rate of fading at 24 \(\mu\)m should be similar to the rate of fading of the heating energy pulse. The surface brightness at the peak position of the infrared (IR) echo within 140 days between 20 August 2007 and 7 January 2008 faded by a factor of 18 ± 3. This can be compared to a brightness decrease by a factor of 17 in the exponentially decaying bolometric light curve of SN 1993J (25) between day 33 and day 173.

It is a historical enigma whether Astronomer Royal Flamsteed witnessed the Cas A supernova on 16 August 1680 at sixth magnitude (26). For the peak visual brightness of ~17.5 mag for SN 1993J (25) and a foreground extinction of \(A_V\) ~ 8 mag, a maximum visual brightness of 3.2 mag would be predicted. This value and the rapid decay (e.g., in sixth magnitude in only 2000 years) are consistent both with the lack of widespread reportage, indicating the peak was fainter than third magnitude (15), and Flamsteed’s observation. The visual extinction varies across the remnant, and we have considered here the most likely extinction value within the plausible range at the center of Cas A (27).

One aspect about Cas A remains puzzling: The progenitor of SN 1993J was a binary star as now confirmed by the detection of a companion (28). A progenitor of 15 to 25 M\(_{\odot}\) that loses its hydrogen envelope to a binary companion and undergoes an energetic explosion is more consistent with the theoretical models and observational constraints for Cas A than an evolved single star undergoing core collapse (15). Although there is at present no evidence for a companion that has survived the explosion (27), it might be speculated that two binary companions merged during a common envelope phase before the explosion (29). The observed asymmetric distribution of the quasi-stationary flocculi (18, 30) near Cas A might originate from the loss of such an envelope.

Lastly, we address one difference between the Cas A supernova spectrum compared with that of SN 1993J: the presence of two unresolved emission lines at 8727 and 9850 Å, which we suggest are from neutral carbon in the interstellar echo cloud. The cloud is located at a distance of 266 ± 23 light years to Cas A [supporting online material (SOM) text]. For the light curve of SN 1993J (25), the peak visual brightness of the Cas A supernova at the location of the cloud is ~12.9 mag, slightly brighter than full moon and leading to a flux density of \(F_{5000\AA}\) ~ 4.9 × 10\(^{-4}\) erg cm\(^{-2}\) s\(^{-1}\) A\(^{-1}\), which is about 1000 times stronger than the interstellar radiation field in the solar vicinity. The color temperature of SN 1993J near maximum light was close to 10,000 K (25). Although the relative flux of Lyman photons capable of ionizing hydrogen is low at such a color temperature, the excitation of carbon lines can still be substantial (31). Carbon is, by a factor of 10, the most abundant atom that can be ionized by photons less energetic than the Lyman limit. Emission lines of carbon are therefore ubiquitous in the predominantly neutral shielded environments of dense interstellar clouds irradiated with ultraviolet (UV)-optical radiation (31, 32). The [C I] transitions at 8727 and 9850 Å lines are known to be the brightest carbon emission lines of photodominated regions in the optical wavelength range (32); however, these lines have so far never been observed as the most prominent lines in supernovae. Thus, it appears likely that the carbon lines are not intrinsic to the supernova spectrum but excited by the UV-optical supernova flash in the echo cloud.

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29 January 2008; accepted 8 April 2008

10.1126/science.1155788