SCATTERED-LIGHT ECHOES FROM THE HISTORICAL GALACTIC SUPERNOVAE
CASSIOPEIA A AND TYCHO (SN 1572)

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Received 2008 March 23; accepted 2008 May 29; published 2008 June 23

ABSTRACT

We report the discovery of an extensive system of scattered-light echo arclets associated with the recent supernovae in the local neighborhood of the Milky Way: Tycho (SN 1572) and Cassiopeia A. Existing work suggests that the Tycho SN was a thermonuclear explosion while the Cas A supernova was a core-collapse explosion. Precise classifications according to modern nomenclature require spectra of the outburst light. In the case of ancient SNe, this can only be done with spectroscopy of their light echo, where the discovery of the light echoes from the outburst light is the first step. Adjacent light echo positions suggest that Cas A and Tycho may share common scattering dust structures. If so, it is possible to measure precise distances between historical Galactic supernovae. Ongoing surveys that alert on the development of bright scattered-light echo features have the potential to reveal detailed spectroscopic information for many recent Galactic supernovae, both directly visible and obscured by dust in the Galactic plane.

Subject headings: ISM: individual (Cassiopeia A, Tycho) — supernova remnants — supernovae: general

Online material: color figures

1. INTRODUCTION

The suggestion that historical supernovae might be studied by their scattered-light echoes was first made by Zwicky (1940) and attempted by van den Bergh (1965, 1966). Our group pioneered the discovery and study of ancient supernova scattered-light echoes using difference imaging in the LMC field where three echo complexes were found to be associated with 400–900 year old supernova remnants (SNRs) (Rest et al. 2005b). We have since obtained a spectrum of one of these echoes which reveals that the echo light is from the class of overluminous Type Ia supernovae (Rest et al. 2008; Badenes et al. 2008) and demonstrates that precise modern supernova classifications are possible for ancient supernovae. These scattered-light echoes preserve optical spectral line information from the outburst, and will be useful for future spectroscopic studies of the original SN light. This is in contrast to the moving Cas A features (sometimes called infrared echoes) identified using far-infrared imagery from the Spitzer Space Telescope (Krause et al. 2005), which are the result of dust absorbing the outburst light, warming and reradiating at longer wavelengths.

Echo features similar to those found in the LMC should be detectable within our own Milky Way. The challenge has been to locate them across a much larger solid angle. We have begun a program to find echoes around a sample of seven certain historical Galactic supernovae recorded in the last 2000 years (Stephenson & Green 2002) (SN 185 AD/Centaurus, SN 1006 AD/Lupus, SN 1181 AD/Cassiopeia, Tycho, Kepler, Cas A). Given the well-constrained ages of these historical supernovae and estimated distances, we can improve our chance to find echoes by targeting regions of cold dust at the approximate expected angular distance. We used the reprocessed 100 μm IRAS images (Miville-Deschênes & Lagache 2005) to select fields with lines of sight which contain such dust, choosing fields closer to the Galactic plane than the supernovae in the expectation that dust would be more highly concentrated there.

Tycho in 1572 discovered one of the last two naked-eye SNe in the Galaxy, while another nearby supernova, Cassiopeia A, evidently escaped discovery around 1671 (Stephenson & Green 2002). Based on the properties of the associated supernova remnants, it is thought that the Tycho SN was a thermonuclear explosion (Ruiz-Lapuente et al. 2004; Badenes et al. 2006) while the Cas A supernova was a core-collapse explosion (Chevalier & Kirshner 1978).

2. OBSERVATIONS AND REDUCTIONS

We obtained images from four observing runs on the Mayall 4 m telescope at Kitt Peak National Observatory in the fall of 2006 and 2007. The Mosaic imager, which operates at the f/3.1 prime focus at an effective focal ratio of f/2.9, was used with the Bernstein VR Broad filter (k1040) which has a central wavelength of 594.5 nm and a FWHM of 212.0 nm. Images of target fields in Cassiopeia were obtained on UT 2006 Oc-
Fig. 1.—Light echo arclets associated with Tycho from field 4821. The direction is north up and east to the left and the images are 325′′ × 250′′. The top panels show the first-epoch image from 2006 October 20 (left) and the second-epoch image from 2007 December 13 (right). The bottom images are the difference images between the two top images where white represents the later (2006 October) image and black the earlier October image. Saturated bright stars are masked gray. In the bottom panels, the left image is repeated in the right panel with the motion vectors plotted. Red represents a straight line fit to the arclet, yellow represents the apparent motion of the arclet, and blue shows the reverse vector direction. The VR surface brightness in the brighter arclets is roughly 24 mag arcsec^{-2}. The widths of the echoes are resolved, and typically 10′′ across.

October 21–23, 2006 December 16, 2007 October 12–15, and 2007 December 13–15. Exposure times were between 120 and 150 s. The interval between the two epochs for a given field is at least 53 days and as much as 2 years. We expect echo arclets to have typical apparent motions of 20′′–40′′ yr^{-1}, meaning a 3 month baseline is sufficient to resolve their apparent motion. Imaging data were kernel- and flux-matched, aligned, subtracted, and masked using the SMSN pipeline (Rest et al. 2005a; Garg et al. 2007; Miknaitis et al. 2007). The resulting difference images are remarkably clean of the (constant) stellar background and are ideal for searching for variable sources.

3. ANALYSIS

Using the same techniques developed for the LMC echo searches (Rest et al. 2005b), candidate echo arclets, such as those shown in Figure 1, were identified by visual examination of difference images.

We estimated the arc motion directions by eye and plotted the inverse motion vectors, as shown in Figure 2a. Two echo complexes were discovered. In the first, we found six clusters of light echoes with proper-motion vectors converging back to the Cas A SNR, and in the other, six more echo clusters consistent with an origin coincident with the Tycho SNR. No echo arclets were detected for SN 1181 during this search, which also lies within our search area, but in a region of lower 100 μm surface brightness. All light echo features discovered seem to be associated with either Cas A or Tycho. We have obtained third- and fourth-epoch images in 2007 for the light echo groups we detected in 2006, and the light echoes were re-detected in these images.

For a given light echo cluster, the vectors have a spread in angle of 10′′ (see Table 1, col. [8]) mainly due to the orientation of the scattering dust: if the reflecting dust sheet or filament is confined to a plane perpendicular to the line of sight, the light echo vector points exactly back to the source. However, if the dust sheet is inclined or warped, then the tangent to the light echo arc may rotate with respect to the perpendicular direction to the remnant position. Provided that the inclinations of dust filaments in azimuth and in distance are not correlated, the average vector will still point in the direction of the SNR. For each light echo cluster, we calculate the average vector (see Table 1), as shown in Figure 2b. The estimated positions for the points of origin for the two echo complexes are listed in Table 2, and calculated as average of the all the pairs of vector crossings (clipped at 3 σ), where the large light blue circles denote the standard deviation of the crossings of all vector pairs in each echo complex. The yellow circles are centered on the Table 2 mean vector crossings and the circle sizes show the error in the mean for the vector crossings.

4. DISCUSSION AND CONCLUSIONS

The light echo equation (Coudert 1939)

$$z = \frac{\rho^2}{2ct} - \frac{ct}{2}$$

relates the depth coordinate z, the echo-supernova distance projected along the line of sight, to the echo distance ρ perpendicular to the line of sight and the time t since the explosion.
The light echo and the associated SNR in degrees. Col. (11): Inferred distance in light years of the dust along the line of sight from the SNR. Cols. (12)–(14): Parameters of the Average Light Echo Arclets and Their Associated Vectors

### TABLE 1

| Field No. | SNR | RA (degrees) | Decl. (degrees) | MJD | N | PA (degrees) | DS | z | RAmín | Decmin | RAmax | Declmax |
|-----------|-----|-------------|----------------|------|---|-------------|----|---|-------|--------|-------|---------|
| 2116      | Cas A | 23 02 42.9 | +56 48 18 | 66.46 | 12 | −117.4 | 16.4 | 3.4 | 431.9 | 23 02 37.7 | +56 44 | 23 02 53.0 | +56 50 50 |
| 2729      | Cas A | 23 13 36.6 | +64 41 15 | 130.77 | 9 | −15.6 | 11.1 | 6.0 | 1374.7 | 23 12 53.9 | +64 40 25 | 23 14 48.1 | +64 42 37 |
| 3024      | Cas A | 23 37 53.6 | +61 42 55 | 116.49 | 6 | 31.0 | 9.5 | 3.4 | 432.3 | 23 37 50.9 | +61 42 27 | 23 37 57.2 | +61 43 17 |
| 3117      | Cas A | 23 45 30.9 | +57 26 51 | 97.86 | 22 | 117.3 | 15.0 | 3.2 | 373.6 | 23 45 11.0 | +57 20 30 | 23 46 13.8 | +57 35 10 |
| 3824      | Cas A | 00 19 03.0 | +61 45 46 | 87.87 | 37 | 73.3 | 11.4 | 7.5 | 1966.7 | 00 18 02.7 | +61 36 10 | 00 19 36.5 | +61 55 45 |
| 3826      | Cas A | 00 17 39.7 | +62 40 59 | 86.44 | 9 | 66.7 | 10.1 | 7.7 | 2034.5 | 00 17 29.5 | +62 39 48 | 00 17 45.1 | +62 44 06 |
| 3325      | Tycho | 23 52 04.4 | +62 03 19 | 170.51 | 6 | −118.2 | 9.1 | 4.3 | 133.9 | 23 52 01.6 | +62 02 35 | 23 52 07.8 | +62 04 20 |
| 4022      | Tycho | 23 08 25.6 | +60 10 14 | 121.57 | 5 | 168.0 | 4.8 | 4.0 | 93.7 | 00 28 20.8 | +60 10 03 | 00 28 30.7 | +60 10 29 |
| 4430      | Tycho | 00 52 10.1 | +65 28 54 | 144.70 | 4 | 52.3 | 7.8 | 3.2 | −18.8 | 00 52 08.5 | +65 28 50 | 00 52 11.3 | +65 28 60 |
| 4523      | Tycho | 00 55 27.1 | +61 10 13 | 227.40 | 17 | 132.2 | 9.0 | 4.6 | 179.4 | 00 55 19.7 | +61 05 08 | 00 55 35.6 | +61 14 58 |
| 4821      | Tycho | 00 17 16.0 | +59 38 37 | 243.77 | 21 | 135.5 | 17.1 | 6.3 | 547.8 | 01 05 03 | +59 31 31 | 01 08 21.8 | +59 44 14 |
| 5717      | Tycho | 01 46 38.0 | +57 13 36 | 216.84 | 10 | 138.0 | 9.3 | 12.1 | 1607.1 | 01 46 29.0 | +57 12 42 | 01 46 50.1 | +57 14 15 |

Notes.—Col. (1): Number of the field in which the light echo was found. Col. (2): SNR associated with the light echo. Cols. (3) and (4): Base position of the vector at the position angle. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (5): Average modified Julian date MJD − 54,000 of the observations. Col. (6): Number of light echo arclets used. Col. (7): Position angle PA in degrees. Col. (8): Standard deviation of the position angles of all vectors in a given light echo cluster, 3 and 4 clipped in order to remove outliers. Col. (9): Angular separation between the light echo and the associated SNR in degrees. Col. (10): Inferred distance in light years of the dust along the line of sight from the SNR. Cols. (11)–(14): Specifications of the box within which a given light echo occurs. All positions are equinox J2000.0.

was observed. Then the distance r from the scattering dust to the SN is \( r^2 = \rho^2 + z^2 \), and \( \rho \) can be estimated with \( \rho \approx D \sin \alpha \), where \( D \) is the distance from the observer to the SN, and \( \alpha \) is the angular separation between the SN and the scattering dust, which yields the 3D position of the dust associated with the arclet. In Figure 3 we see that three of the six Cas A light echo clusters (fields 2116, 3024, and 3117) are at very similar distances at \( z \approx 400 \) lt-yr in front of Cas A. This clustering of \( z \) suggests that these three clusters are associated with the same extended dust sheet/filament. Similarly, two other Cas A light echo clusters (fields 3824 and 3826) are likely from a single dust structure at \( z \approx 2000 \) lt-yr. For Tycho a number of arclets (fields 3325, 4022, 4430, and 4523) are found near \( z \approx 100 \) lt-yr (relative to the Tycho SNR) and one field, 5717, contains scattering dust at \( z \approx 1600 \) lt-yr.

The distance to Tycho and Cas A is estimated to be \( 2.3 \pm 0.5 \) and \( 3.4 \pm 0.5 \) kpc, respectively (Albinson et al. 1986; Strom 1988; Lee et al. 2004; Reed et al. 1995). This implies that Cas A is \( 3600 \pm 2300 \) lt-yr behind Tycho. For both Cas A and Tycho, there is a clustering of the scattering dust structures in \( z \), indicating that there are extended dust structures or sheets, in contrast to small, local dust structures. The Tycho scattering dust structures cluster around \( z = 0 \), implying that they are also in front of Cas A. Since Cas A is in close angular proximity to Tycho, it can be expected that dust belonging to this extended dust structure produce light echoes for both Tycho and Cas A. Thus we explore the possibility that Cas A and Tycho share extended scattering dust structures. It is notable that the difference between the outer and the inner dust structures is about 1500–1600 lt-yr for both Cas A and Tycho. Thus one scenario is that the Tycho light echo groups

### TABLE 2

| SNR Parameters |
|----------------|
| SNR (1) | RA(SNR) (2) | Decl(SNR) (3) | RA(origin) (4) | Decl(origin) (5) | \( \delta r \) (6) |
| Cas A | 23 23 24 | +58 48 54 | 23 25 16 | +58 46 43 | 6.2 |
| Tycho | 00 25 08 | +64 09 56 | 00 27 58 | +64 03 25 | 14.5 |

Notes.—Cols. (2) and (3): Radio positions of the SNR likely associated with the light echo group. Cols. (4) and (5): Averaged position of the vector crossing points. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (6): Uncertainties in the position, given in arcminutes. Coordinates are equinox J2000.0.

![Fig. 3.—Distance \( z \) from the supernova to the scattering cloud projected along our line-of-sight plotted with respect to the position angle from the associated supernova remnant. To calculate \( z \), we assume that the distance to Tycho is 2300 pc and for Cas A 3400 pc. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
which corresponds to distances spread around $z = 0$. Such a situation may exist for Tycho (see Fig. 3). In the worst case, the distance $D_{\text{Tycho}}$ may be significantly larger than the current estimate of 2300 pc (Albinson et al. 1986; Strom 1988; Lee et al. 2004) and a strong lower limit on the distance of Tycho may be set. If Tycho is nearer than the current estimate, a more accurate distance is possible since the distance of the scattering dust will then bracket the supernova distance. For Cas A, none of our detections imply scattering dust behind the SNR (see Fig. 3). However, the existence of reradiated echo light in the infrared (Krause et al. 2005) suggests that such echoes may yet be detected.

For Cas A and Tycho, 5% and 3%, respectively, of the fields surveyed within $z < 2000$ lt-yr contain scattered-light echo ar- clets (see Fig. 4, top and middle panels). Virtually all light echoes are found at $z < 2000$ lt-yr, and in particular at 0 lt-yr < $z < 500$ lt-yr. No light echoes from SN 1181 (3C 58) were detected. On first glance this is surprising. However, the bottom panels reveal that we have searched a smaller fraction of the 0 lt-yr < $z < 500$ lt-yr, forward-scattering region of SN 1181 in comparison to Cas A and Tycho. A combination of fainter surface brightness of the light echoes due to the supernova age and brightness and small-number statistics might explain the lack of detections. Deeper surveys of the SN 1181 region might yet yield light echoes. Light echoes are expected to be scattered light of the averaged flux around maximum luminosity; the only significant modification of the event outburst light is expected to be due to dust grain size which, in the absence of additional absorption along the echo paths, makes the spectral flux bluer. We have demonstrated that the type of a SN (Ia, II, etc.) and the subtype (luminous, normal, underluminous Type Ia) can be determined centuries after the event by taking a spectrum of the light echo (Rest et al. 2005b, 2008).

In the Milky Way Galaxy alone there have been at least seven historic SNe (Stephenson & Green 2002) that are good candidates to have produced still-observable light echoes. Other apparently young SNRs identified in radio and X-ray surveys exist in the plane of the Galaxy (Green & Gull 1984; Reynolds et al. 2008) that have no historical records, most likely because they are obscured by dust. Light echoes of these obscured SNe may be visible since the line-of-sight to scattering dust may be less obscured than direct light. Potentially, dozens of ancient SNe can be typed by the means of light echo spectroscopy as described in Rest et al. (2008). We note that this is one of the very rare occasions in astronomy for which cause and effect of the same astronomical event can be observed, in that we can study the physics of the SNR as it appears now and also the physics of the explosion which produced the SNR as it appeared hundreds of years ago.

The study of scattered-light echoes from Galactic SNe provide a host of newly recognized observational benefits which have only just begun to be exploited, including the capacity to understand the connection between remnant properties and the outburst spectral type, access to observables related to asymmetric explosion properties, and a network of absolute distance differences.

We dedicate this Letter to Howard Lanning, who passed away 2007 December 20. A. R. thanks the Goldberg Fellowship Program for its support. D. W. acknowledges support from the National Sciences and Engineering Research Council of Canada (NSERC). SuperMACHO was supported by HST grants GO-10583 and GO-10903. This work was partially performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory in part under contract W-7405-Eng-48 and in part under contract DE-AC52-07NA27344. N. B. S. thanks S. van den Bergh for the suggestion in 1995 to search for echoes using CCDs. NOAO is operated by AURA under cooperative agreement with the NSF.

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