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

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ABSTRACT

We report the discovery of an extensive system of scattered light echo arclets associated with the recent supernovae in the local neighbourhood 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. On-going 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(Cas A) — ISM: individual(Tycho) — supernova:general — supernova remnants

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, 1975). 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 (SNR) (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 over-luminous Type Ia supernovae (Rest et al. 2008; Badenes & Bravo 2008) and demonstrating 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 re-radiating 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 7 certain historical Galactic supernovae recorded in the last 2000 years (Stephenson & Green 2002) (SN 185 AD/Centaurus, SN 1054 AD/Crab, SN1006 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 & REDUCTIONS

We obtained images from four observing runs on the Mayall 4m telescope at Kitt Peak National Observatory

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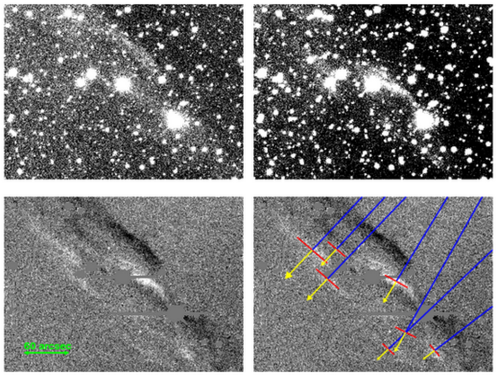

FIG. 1.— Light echo arclets associated with Tycho from field #4821. The orientation is N up and E to the left and the images are 325 x 250 arcseconds. The upper two panels show the first epoch image from 20 October 2006 (left), and the second epoch image from 13 December 2007 (right). The lower images are the difference images between the two upper images where white represents the later (October 2006) image and black the earlier December image. Saturated bright stars are masked gray. In the lower panel, 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.

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 594.5nm and a FWHM of 212.0nm. Images of target fields in Cassiopeia were obtained on UT 2006 Oct 21-23, 2006 Dec 16, 2007 Oct 12-15, and 2007 Dec 13-15. Exposure times were between 120 and 150 seconds. The interval between the two epochs for a given field is at least 53 days and as much as two years. We expect echo arclets to have typical apparent motions of 20-40 arcsec yr^{-1}, meaning a 3-month baseline is sufficient to resolve their apparent motion. Imaging data was 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 panel *A* of Figure 2. 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 micron surface brightness. All light echo features discovered seem to be associated with either Cas A or Tycho. We have obtained 3rd and 4th epoch images in 2007 for the light echo groups we detected in 2006, and the light echoes were redetected in these images.

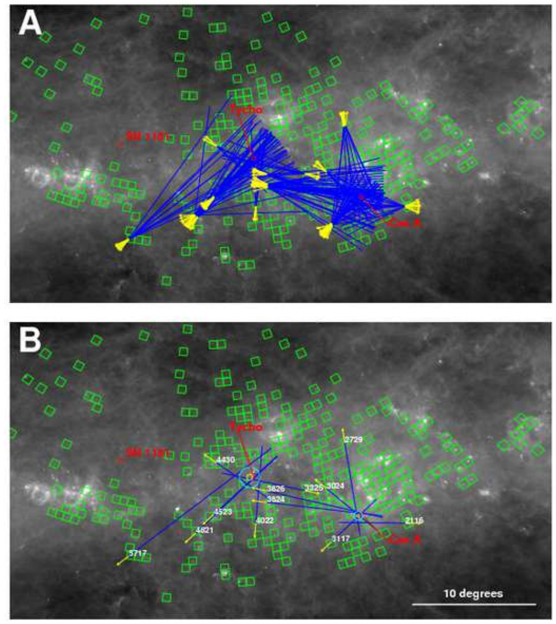

FIG. 2.— Arclet vector motions in the region of Cas A and Tycho supernovae. The vectors are plotted on an image reconstructed from IRAS data at 100μm (Miville-Deschênes & Lagache 2005). The panels are $44^{\circ} \times 25^{\circ}$ with N up and E to the right. The green squares show the Mosaic fields where we have at least two epochs and have been searched for arcs in the difference image. The red circles mark the positions of the three historic SNe SN 1181, Tycho, and Cas A. There are six clusters of light echoes with apparent motion vectors pointing back to the Cas A SNR, and six more consistent with an origin coincident with the Tycho SNR. Panel B shows the average vector for each light echo cluster. The apparent 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-sigma) 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.

For a given light echo cluster, the vectors have a spread in angle of 10 degrees (see column PA(stdev) in Table 1) mainly due to the orientation of the scattering dust: If the reflecting dustsheet 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 dustsheet 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 panel *B* of Figure 2. The estimated positions for the points of origin for the two echo complexes are given in Table 2 as calculated by the average of all pairs of vector crossings (clipped at 3-sigma). The Tycho and Cas A SNR positions are within the standard deviation of the points of origin and within 3-sigma of the average position.

4. DISCUSSION & CONCLUSIONS

The light echo equation (Couderc 1939)

$$z = \frac{\rho^2}{2ct} - \frac{ct}{2} \quad (1)$$

TABLE 1

Field# (0)	SNR (1)	RA (2)	Dec (3)	MJD (4)	N (5)	PA (6)	PA(stdev) (7)	DS (8)	z (9)	RAmin (10)	Decmin (11)	RAmax (12)	Decmax (13)
2116	CasA	23:02:42.9	+56:48:18	66.46	12	-117.4	16.4	3.4	431.9	23:02:37.7	+56:44:11	23:02:53.0	+56:50:50
2729	CasA	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	CasA	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	CasA	23:45:30.9	+57:26:51	97.86	22	117.3	15.0	3.2	373.6	23:45:11.0	+57:20:50	23:46:13.8	+57:35:10
3824	CasA	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	CasA	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	00:28:25.6	+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	01:07:11.6	+59:38:37	243.77	21	135.5	17.1	6.7	547.8	01:05:48.7	+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

NOTE. — This Table lists the parameters of the average light echo arclets and their associated vectors. The column Field# shows the number of the field in which the light echo was found. The column SNR indicates the SNR associated with the light echo. RA, Dec define the base position of the vector at position angle of PA in degrees. MJD indicates the average modified Julian date MJD - 54000 of the observations. The column N shows how many light echo arclets where used. The column PA(stdev) is the standard deviation of the position angles of all vectors in a given light echo cluster, 3-sigma clipped in order to remove outliers. Column DS shows the angular separation between the light echo and the associated SNR in degrees. The inferred distance z in light years of the dust along the line of sight from the SNR is shown in column z. The light echoes of a given light echo cluster are within the box specified by RAmin, DECmin, RAmax, DECmax. All positions are equinox J2000.0

TABLE 2

SNR (0)	RA(SNR) (1)	Dec(SNR) (2)	RA(origin) (3)	Dec(origin) (4)	δr (5)
Cas A	23:23:24	+58:48:54	23:25:16	+58:46:43	6.2
Tycho	00:25:08	+64:09:56	00:27:53	+64:03:25	14.5

NOTE. — RA(SNR) and Dec(SNR) are the radio positions of the SNR likely associated with the light echo group. RA(origin) and Dec(origin) are the averaged position of the vector crossing points. The uncertainties δr in the position are given in arcminutes. Coordinates are equinox J2000.

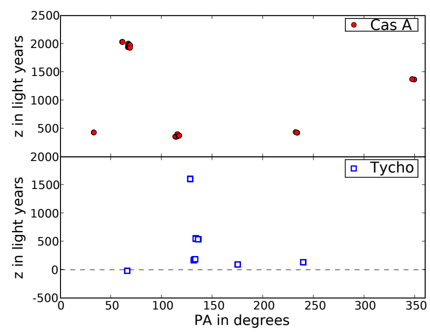

FIG. 3.— The distance z from the supernova to the scattering cloud projected along our line-of-sight plotted with respect to the position angle from the associated supernova remnant. To calculate z, we assume that the distance to Tycho is 2300pc and for Cas A 3400pc.

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

The distance to Tycho and Cas A is estimated to be 2.3±0.5kpc and 3.4±0.5kpc, respectively (Albinson et al. 1986; Strom 1988; Lee et al. 2004; Reed et al. 1995). This implies that Cas A is 3600 ± 2300 light years 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 there are also in fron 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 light years for both Cas A and Tycho. Thus one scenario is that the Tycho light echo groups in field #3325, #4022, #4430, and #4523 and Cas A light echo groups in field #2116, #3024, and #3117 belong to the same dust structure, and Tycho #5717 and Cas A #3824 and #3826 to another dust structure. Since the measured z distance is always relative to its associated SNR, this would then imply that Cas A is about 300-400 light years farther away than Tycho, which is not within 1 sigma of the current estimate of 3600 ± 2300 light years. Another possibility is that the outer Cas A light echo cluster in fields #3824 and #3826 arise from the same extended dust structure which causes the Tycho light echoes in field #3325, #4022, #4430, and #4523. This association seems more likely due to the close proximity of these two arc groups on the sky. For this association, Cas A must be 1900 light years more distant than Tycho, which is within the errors of the current estimates.

Geometric light echo distance estimates are possible when the scattering angle is known (e.g. Sparks et al.

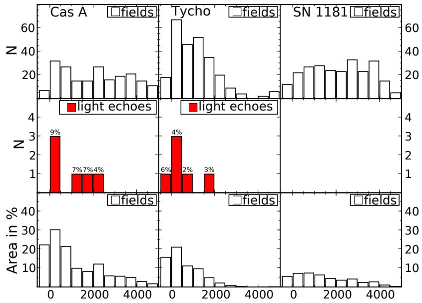

FIG. 4.— Histograms of the number of fields with two epochs versus their distance z along the line of sight (i.e., how much in front or in back of the supernova the scattering dust is) to the SNRs Cas A, Tycho, and SN 1181 from left to right in the upper panels. The middle panels show the number of light echo groups found in a given z bin. The percentage of fields with light echoes for a given bin is shown above the red bars in percent. The bottom panels show the % of the total area (i.e. the annulus associated with the given z bin) is covered by the observed fields.

(2008) for V838 Mon). A maximum in the linear polarization is expected for an angle of 90° - when the scattering dust is at the same distance as the supernova. Therefore this method works best with light echoes with scattering angles spread around 90°, which corresponds to distances spread around $z = 0$. Such a situation may exist for Tycho (see Figure 3). In the worst case, the distance D_{tycho} may be significantly larger than the current estimate of 2300pc (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 Figure 3). However, the existence of re-radiated 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% of the fields surveyed with $z < 2000$ light years contain scattered-light echo arclets, respectively (see upper and middle panels of Figure 4). Virtually all light echoes are found at $z < 2000$ light years, and in particular at $0 < z < 500$ light years. No light echoes from SN1181 (3C58) were detected. On first glance this is surprising. However, the bottom panels reveal that we have searched a smaller fraction of the $0 < z < 500$ light year, forward-scattering region of SN1181 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 SN1181 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 7 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 that 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.

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