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Research Note

Minutes timescale search for a pulsar in SNR 1987 A*

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Abstract. We have searched for minutes to hours timescale optical modulation from SNR 1987 A due to occultation of the putative neutron star by passing dust clouds. For this study, photometric images of the supernova were taken at one minute intervals using the NTT at ESO. We did not detect significant optical variability on this timescale from the supernova against the background of the two nearby stars. Based on our findings, we cannot rule out the possibility of an optical pulsar. However, if the neutron star is temporally obscured, we set an upper limit on the magnitude of the pulsar in the *R* band 20.1.

Key words: supernovae: SN 1987 A – pulsars

1. Introduction

Neutron stars are believed to be the core remains of type II supernovae. The explosion of Sanduleak $-69°202$ in the LMC has given us a unique opportunity to study the final phase of stellar evolution and verify the creation of a neutron star. The development of the light curve, and the observed absorption of the Balmer lines indicate that SN 1987 A was type II, and the neutrino burst observed by both Kamiokande (Bionta et al. 1987) and IMB (Hirata et al. 1987) provide strong evidence that a neutron star was formed at the time of the explosion (Burrows 1989). The birth properties of neutron stars are largely unknown and the detection of a pulsar would directly confirm the theoretical scenarios. Also, if a neutron star is found in the remnant of the supernova 1987 A, it will be the first compact object with a previously observed progenitor star.

An optical search provides the best hope for peering into the remnant at this time. The nebula is believed to be mostly opaque to both X-ray and radio wavelengths, where the optical depths are estimated by McCray (1993) to be $\tau_x \approx 300 t_{year}^{-2}$, $\tau_r \approx 0.1 \lambda_{cm}^2 t_{year}^{-2}$. Several attempts have been made to detect pulsed radiation from the remnant. The optical searches using ESO facilities gave limits of about 21.5 magnitude for pulsations from 0.1-5000 Hz (Ögelman et al. 1990). The more recent HST observation (Percival et al. 1995) and the data from AAT (Manchester & Peterson 1996) have set the limit at around $V \sim 24$ for fast optical pulsations.

The lack of a fast pulsating signal from the supernova remnant may be due to several possibilities:

1. The fast pulsations may be shorted out if there is a large amount of accretion back onto the neutron star. The heating of the neutron star caused by infalling matter could give rise to thermomagnetic effects which may weaken the magnetic field of the neutron star (Blondin & Freese 1986).
2. The pulsar may be beaming but not in our line of sight. The beamed radiation from the putative pulsar should nevertheless interact with the surrounding nebula. The current bolometric luminosity of the SN 1987 A (Suntzeff et al. 1992) is comparable to the spin-down luminosity of the Vela pulsar $\sim 10^{36.8}$ ergs s^{-1}.
3. The optical luminosity of pulsed emission from near the pulsar light cylinder is believed to be proportional to $B_\circ^4 P^{-10}$ (Pacini 1971). The statistical study of pulsar population and the study of PSR 1951+32 show young pulsars may be born with long periods ($P \sim 0.5$ s) and weak surface magnetic fields ($B_\circ \sim 5 \times 10^{11}$ G) (Narayan 1987, Foster et al. 1990). Pulsed emission from such stars are beyond the current search sensitivities and SN 1987 A also may be pulsing below the sensitivity limit.
4. The material surrounding the pulsar may absorb most of the radiation. The detection of the infrared continuum radiation as early as day 350 confirms dust formation in the supernova envelope (Danziger et al. 1989, Meikle et al. 1993). The ejecta from the supernova were subject to Rayleigh-Taylor instabilities, as evidenced by the mixing of heavy elements from the low velocity core to the high velocity outer envelope (Erickson et al. 1988, Witteborn et al. 1989,

* Observations made at the European Southern Observatory, La Silla, Chile

Tueller et al. 1990). The spectroscopic measurements of iron and nickel lines (Spyromilio et al. 1990, Haas et al. 1990) and the unexpected early emergence of 16-28 KeV X-rays (Kumagai et al. 1989) however imply the distribution of material around the supernova is not distributed uniformly, but is concentrated in clumps.

Our study focuses on the possibility of optical variability caused by such dust and gas formations passing across our line of sight. A model (Li & McCray 1993) to account for Fe, Co, and Ni emission lines has been developed that assumes the presence of gaseous clumps within the expanding ejecta. From the emission line widths, the velocities of the clumps have been measured to be $\sim$ 2500 km s^{-1}. We estimate a clump of similar cirumstellar gas cloud with such velocity could occult the neutron star and may cause luminosity variations of the supernova remnant core on time scale of minutes to hours. In this letter we report the result of this new approach in the optical search for the putative pulsar performed at ESO.

2. Observation and analysis

SN 1987 A was observed on 1991 October 1st, using European Southern Observatory (ESO) 3.5m New Technology Telescope (NTT). The EMMI (ESO MultiMode Instrument) red arm was used which afforded a 0.″44/pixel resolution, but the seeing at the time was not optimal. A series of one minute exposures were taken at one minute intervals one using the broadband red filter. The images were bias and flat-field corrected using the standard procedure.

The supernova is flanked by two stars. Using the notation from Walker & Suntzeff (1990), star 2 is 2.″90 away at position angle 135° with V magnitude of 15; star 3 is a Be variable (Walborn et al. 1993) located 1.″66 away at position angle 57° with V magnitude of 16. The stellar images on the CCD frames are heavily overlapped, necessitating the use of profile fitting (Fig. 1). The images were initially reduced using ALLSTAR attachment to DAOPHOT (Stetson 1987). The program determines the point spread function (PSF) from other stars in the field and simulataneously fits the profiles. We found that this technique was inadequate, because at the time of our observation, the light from the circumstellar ring around the supernova had become comparable to the supernova itself (Caldwell et al. 1993). We devised a profile fitting program similar to DAOPHOT that took into account the elliptical circumstellar ring. The ring was modeled with fixed inclination and the semimajor and semiminor axes set at 0.″83 and 0.″61 (Jakobsen et al. 1991), centered on the supernova. The peak intensity and the FWHM were left as varying parameters. The stars in the field were fit using a hybrid analytic bivariate Gaussian function with an empirical lookup correction table. In each CCD frame, six stars were chosen to generate the PSF and the residual lookup table. The two nearby stars, the supernova and the circumstellar ring are then simultaneously fit in position and magnitude. The reduced χ^2 of the CCD frames varied from 0.6 to 1.3. Each frame is normalized by determining the magnitude differences of the PSF stars from their time averaged values.

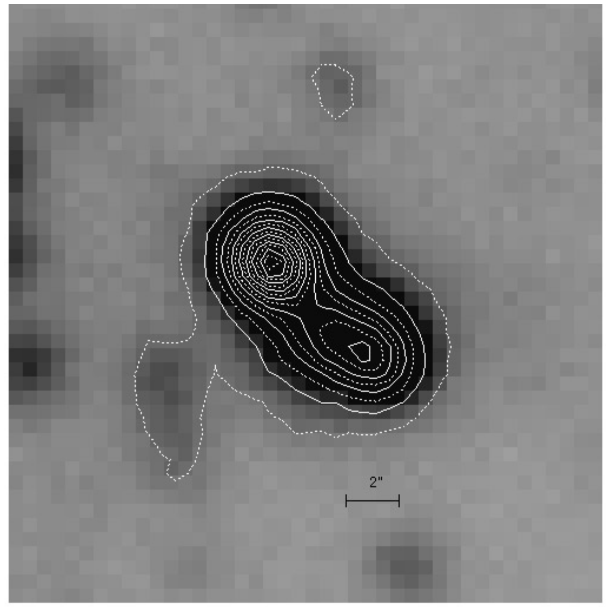

Fig. 1. Optical contour image of the supernova and stars 2 and 3. The horizontal line represents 2″

Table 1. Photometry for stars 2 and 3. The results presented here taken at ESO, and the results from SAAO (Caldwell et al. 1993) and CTIO (Walker & Suntzeff 1991)

Star	ESO	SAAO	CTIO
2	15.028 ± 0.009	15.032 ± 0.006	15.01
3	15.869 ± 0.043	15.889	15.57

3. Results and discussion

The time averaged magnitudes of stars 2 and 3 were measured and presented in Table 1. Fig. 2 shows the tracked luminosity of the combined supernova and the circumstellar ring (SN clump) through all the CCD frames. Our magnitude measurements are in good agreement with the SAAO results (Caldwell et al. 1993). The CTIO group gave a lower magnitude measurement for star 3 perhaps because the NSTAR option to DAOPHOT does not account for the bright inner ring (Walker & Suntzeff 1991).

We are unable to confirm the optical variation on the timescales of minutes from the supernova remnant from our data. The significant light contribution from the ring and the limited angular resolution of the ground based detector did not allow us to resolve the central remnant, thus we are only able to limit the uncertainty of the light variation of the supernova to $\sim 3\%$. If a dust cloud or accreting matter is occulting the central compact object, we set an upper limit to the magnitude of the compact object in the R band $\gtrsim 20.1$, based on the magnitude of the SN clump at the time of our observation.

Although we do not see optical modulations due to the pulsar, we cannot rule out the possibility of its existence. The optical luminosity due to the surface emission from the Vela pulsar is

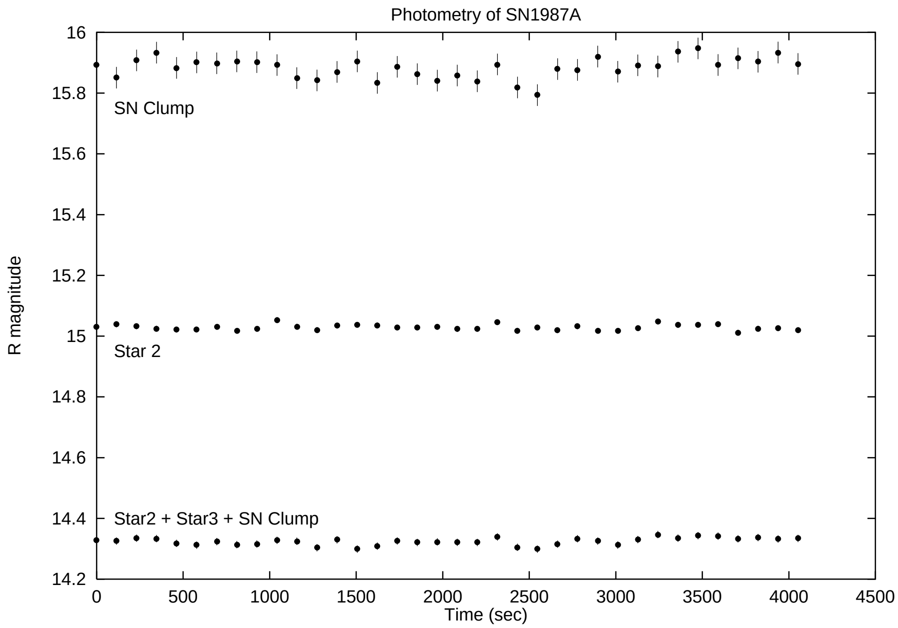

Fig. 2. Photometry of the SN Clump. The photometry of star 2 and the combined flux from all three stars are also shown. One standard deviation error bars are plotted. The photometry of star 3 was omitted for clarity.

$\sim 5 \times 10^{28}$ergs s^{-1}, which gives an apparent magnitude of V $\sim$ 23 at a distance of only 500 pc. The short duration ($\sim$ 2 hours) of our observation may have limited the sensitivity of our search since we do not know the actual timescale of pulsar occultation. Also, a higher density of gas and dust may exist in the vicinity of the central compact object which will absorb much of the radiation from the embedded pulsar.

As the supernova remnant expands, the optical depth of the nebula will continue to decrease. In the ten years after the explosion, the remnant has expanded to few tenths of an arcsecond in the visible. It is important to resolve the inner structure of the remnant to further increase our sensitivity to optical modulations from the remnant. Using facilities such as the HST, it may be possible to resolve the clumpy region near the compact object. A continued search for the putative pulsar in SN 1987 A is certainly worthwhile.

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