On the Optical Counterpart of PSR 0540-693

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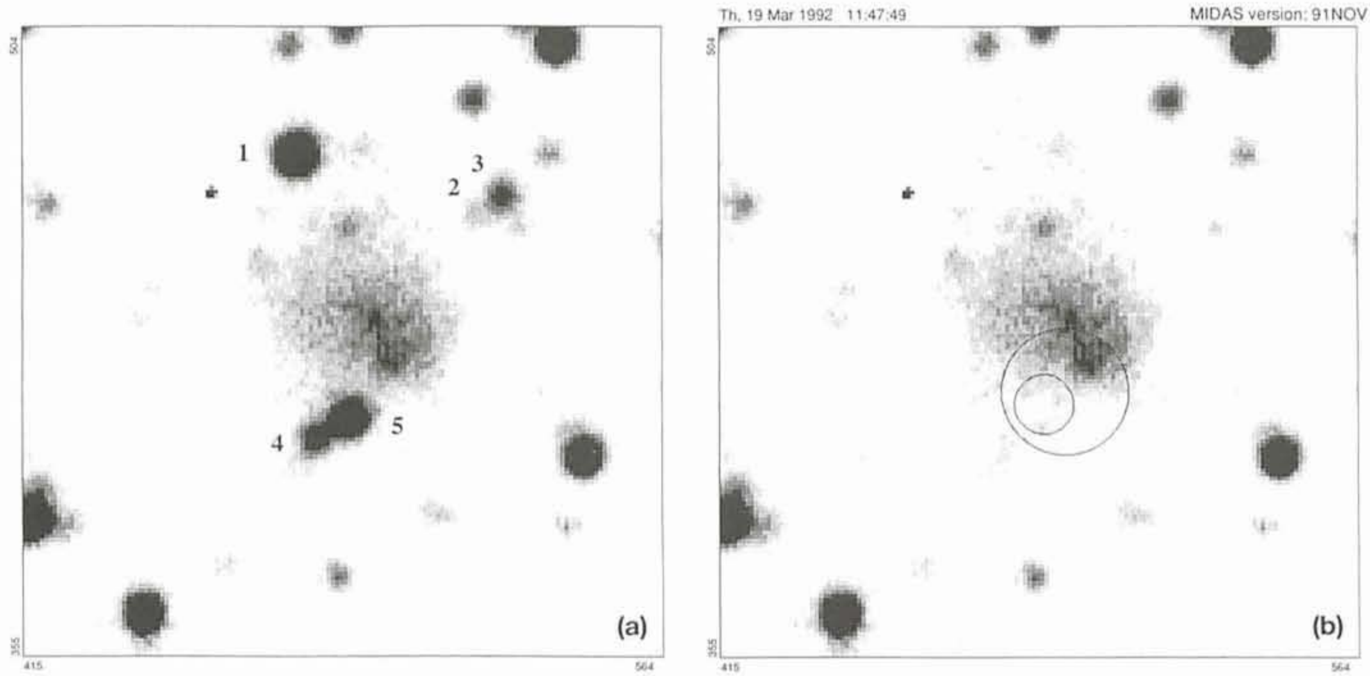
Part of the remnant of the penultimate known supernova explosion in the Large Magellanic Cloud, PSR 0540-693, is the only "classical" young pulsar not seen in radio because of its distance. Nevertheless, X-ray and optical studies of this object, as well as of the surrounding SNR, classify it as the most striking example of a Crab-like SNR-pulsar association.

Like the Crab, SNR 0540-693 does contain a $\nu^{-0.8}$ power-law spectrum radio to X-ray synchrotron nebula (Chanan et al., 1984, Clark et al., 1982), where the Einstein Observatory discovered the 50-msec pulsation of PSR 0540-693 (Seward et al., 1984), contributing ~23 % of the total unresolved X-ray emission. Although below the current detectability limit of the southern hemisphere radio telescopes, the object has been seen as an optical pulsar (Middleditch and Pennypacker, 1985; Middleditch et al., 1987) with B and V magnitudes ~22 and colours slightly redder than those of the Crab pulsar.

After Crab and Vela, PSR 0540-693 is thus the third pulsar detected as a fast pulsating optical source.

However, partly because of the lack of precise position (usually computed from long-term radio timing data) and partly because of lack of high-resolution



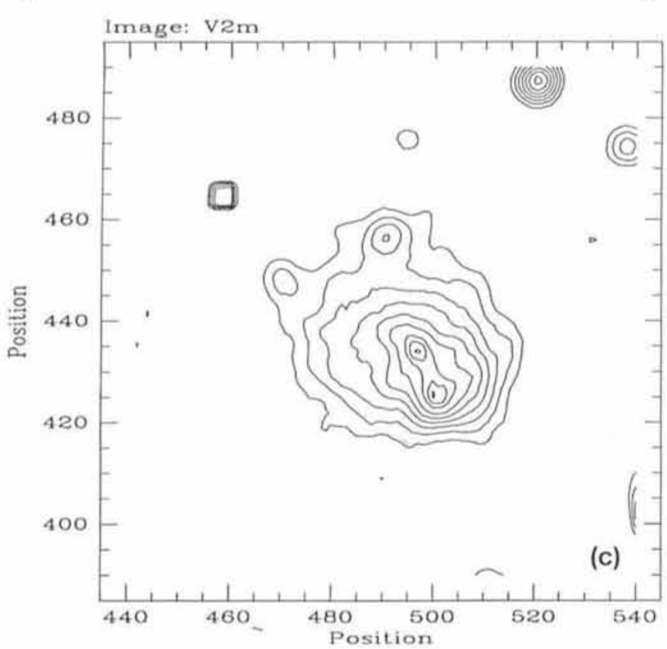


Figure 1: *Data analysis sequence for the 2-minute V filter image of SNR 0540-69 in LMC, taken at the ESO NTT under sub-arcsec seeing conditions. North is up, east at left.*
(a) raw data after flat fielding. The star images visible near the SNR are labelled 1-5. The SUSI/NTT pixel size is 0.13". Frame scale in pixels.
(b) as (a), after subtraction of stars 1-5. The 4" diameter error circle represents the HRI position of the Einstein X-ray pulsating source 1E 0540.5-6921, while the 1.8" diameter circle has been computed by Manchester and Peterson (1989). Of the two maxima observed, the northern (central) at the boundary of the X-ray circle, appears more compact and is our proposed counterpart for the 50-msec pulsar.
(c) Isophote map of (b). Low flux contour to the north-east of the remnant could arise from unrecognized faint field stars.

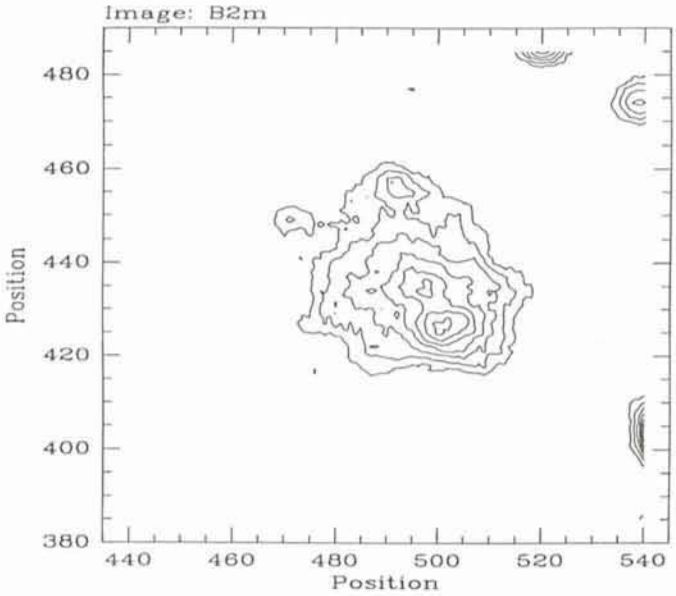


Figure 2: *Isophote map, after subtraction of stars 1-5, of the 2-minute B filter image.*

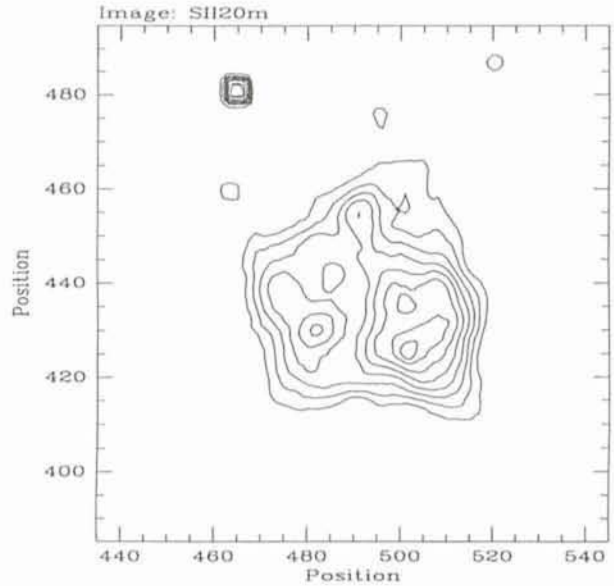


Figure 3: *Star subtracted isophote map of 20-minute SII (λ=6728 Å, $\Delta\lambda$=59 Å) image.*

optical data, it has so far been impossible to optically identify its counterpart against the background of the synchrotron nebula.

With an angular diameter of ~10″ and an integrated diffuse emission far brighter than the pulsing source, PSR 0540-693 and its Synchrotron nebula are indeed a challenging target for high-resolution imaging.

Nevertheless, in the absence of a radio signal (a condition unique to this object), the optical identification would be the *only* way to know its precise position. This is a critical piece of information for long-term temporal studies, such as the measure of the braking index, a key parameter for the understanding of the pulsar emission mechanisms, known, so far, only for PRS 0530+21, the Crab pulsar, and PSR 1509-58, the "150-msec" pulsar. The Crab-like young pulsar PSR 0540-693 would indeed be a prime candidate for a precise measure of the braking index because of its high $\dot{P}$. The results are, however, inconclusive, mainly because of the uncertainties induced by the ± 2″ positional error in the barycentrization of the pulsed photon arrival times, a procedure needed to phase correctly light curves collected at different epochs.

The resolving power needed to start on this problem has been provided by SUSI (SUperb Seeing Imager, pixel size of 0.13″ over a field of view of 2.2×2.2 arcmin) on November 1991, under sub-arcsec seeing conditions, as part of the ESO Key Programme 6-002-45K.

We obtained two 1-minute V exposures, one 2-minute B exposure, one 10-minute Hα (λ=6552 Å, $\Delta\lambda$=60 Å) exposure, two 10-minute and one 40-minute OIII (λ=5015 Å, $\Delta\lambda$=55 Å) exposures, and one 20-minute SII (λ=6728 Å, $\Delta\lambda$=59 Å) exposure, during two nights with seeing conditions varying from 0.6 to 0.9 arcsec.

The choice of filters was suggested by the previous imaging and spectroscopy work done on this object (Mathewson et al., 1980, Dopita and Touhy, 1984; Chanan et al., 1984; Kirshner et al., 1989). Our data-analysis procedure was as follows: after the usual cleaning and flat fielding, the five stellar images nearest to 0540 were subtracted in order to avoid their contribution to the diffuse structures, and a standard isophote image was constructed. Figure 1 (a, b and c) show such process for the V filter. The same star subtraction routine was than applied to the B as well as the narrow-band filter images, and the resulting isophote maps are given in Figures 2, 3, 4 and 5 for B, SII, OIII and Hα, respectively. The 4″ circle in Figure 1 represents the error region associated with the HRI X-ray source, 1E 0540.5-6921, located at $\alpha_{(1950)}$ = $5^h40^m33.9^2$ $\delta_{(1950)}$ = -69°21′23″.2 with the 2″ accuracy reported in the discovery paper by Seward et al., 1984. The nominally more accurate position, at $\alpha_{(1950)}$ = $5^h40^m34.03^s$ $\delta_{(1950)}$ = -69°21′23″.5, with a 0.9″ uncertainty, obtained by Manchester and Peterson (1989) on the basis of pulsar timing, has been added for completeness, in spite of later criticism by Nagase et al., 1990. Our astrometry was performed using several stars extracted by the Guide Star Catalogue and kindly provided to us by the User Support Branch of the STScI. We estimate its r.m.s. error to be less than 0.4 arcsec.

Two distinct maxima are visible inside the nebula in our B and V images, and the northern one appears more point-like. They are located, respectively, at $\alpha_{(1950)}$ = 5^h 40^m 33.84^s (± 0.5″) $\delta_{(1950)}$ = -69°21′20.9″ (± 0.5″), where the estimated error is mainly due to our astrometry, and $\alpha_{(1950)}$ = 5^h 40^m 33.78^s (± 1.0″) $\delta_{(1950)}$ = -69° 21′ 21.9″ (± 1.0″), where the estimated error comes mainly from the uncertainties in the centring algorithm.

Both positions appear compatible with the X-ray error box as well as with that of the 4.6″ diameter aperture used by Middleditch and Pennypacker (1985) to search for (and find) the optical pulsations.

Moreover, the B and V magnitudes of our two maxima are both compatible with the time-averaged values obtained

Table 1

	V filter	B filter
Northern maximum	22.4 ± 0.2	23.6 ± 0.3
Southern maximum	22.6 ± 0.2	23.0 ± 0.3
Pulsar (Middleditch and Pennypacker, 1985)	22.26 ± 0.20	23.15 ± 0.20
Pulsar (Middleditch et al., 1987)	22.38 ± 0.14	22.76 ± 0.23

The values reported in this table have not been corrected for interstellar absorption.

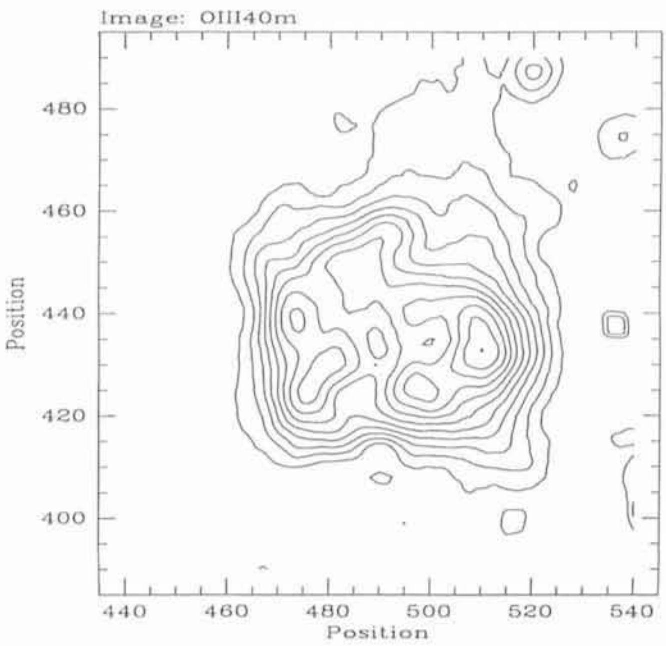


Figure 4: *Star subtracted isophote map of the 40-minute OIII ($\lambda = 5015$ Å, $\Delta\lambda = 55$ Å) exposure.*

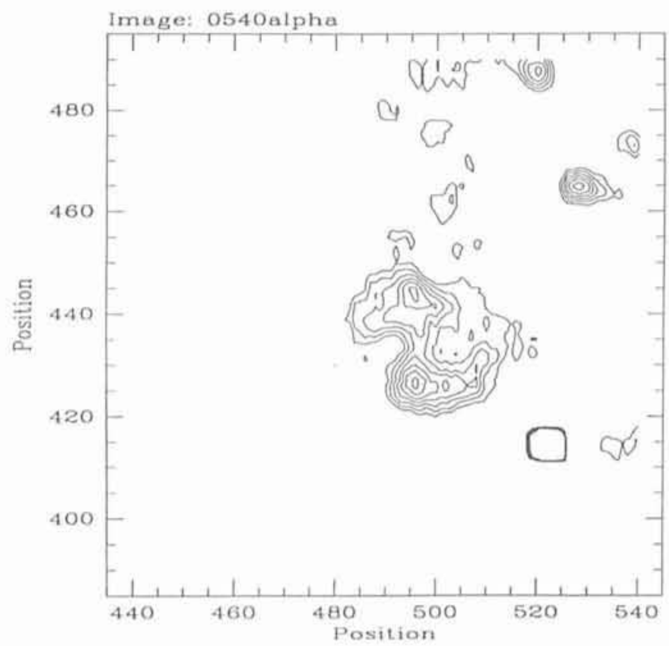


Figure 5: *Star subtracted isophote map of the 10-minute Hα ($\lambda = 6552$ Å, $\Delta\lambda = 60$ Å) image.*

during the fast photometry studies (see Table 1). This would imply for PSR 0540-693 a pulsed fraction near 100 %, to be compared with values of 75 % for the Crab and ~50 % for Vela. However, our magnitude estimates are uncertain because of the presence of the extended emission and any conclusion has to be taken with caution.

Besides identifying these two potential counterparts of PSR 0540-693, our data confirm the previous findings on the expanding shell as well as on the continuum synchrotron nebula. They also add considerable detail on the structure of both (see Caraveo et al. 1992 for a complete account of the results). The Hα image, not available in the literature so far, shows a structure smaller than that of the synchrotron nebula and with a totally different shape. The dimension of the "major axis" of the remnant, as seen in the different filters, varies from 9" in OIII to 7.5" in SII to 5.5" in the continuum to a bare 4" in Hα.

While our results on the dimension, shape and brightness of the remnant in B, V, OIII and SII come as no surprise, the Hα picture is somewhat intriguing. Our isophote map suggests either a ring seen edge-on, not dissimilar from the OIII ring of 1987A, or some kind of jet-like structure. The symmetric pattern outlined by the Hα image appears to be centred on the northern maximum we have described above. This is shown in Figure 6, where the outer contours of the remnant seen in the OIII, Hα and in V filters have been superimposed to the position of the two maxima.

The northern object is clearly favourite because of its more compact appearence as well as of its central position with respect to the remnant as a whole and to the Hα structure, which seems to originate from it.

A high resolution U exposure of the remnant is required to confirm the proposed optical counterpart of the pulsating source, which is known to be particularly bright in U (Middleditch et al., 1987).

PSR 0540-693 would thus be the third case of an optically identified neutron star, providing a nice example of the capability of the NTT equipped with SUSI.

References

Caraveo, P.A., Bignami, G.F., Mereghetti S. and Mombelli M. 1992 *Ap.J.* (Letters) in press.

Chanan, G.A., Helfand, D.J. and Reynolds, S. 1984, *Ap.J.* (Letters), **287**, L23.

Clark, D.H., Tuohy, I.R., Long, K.S., Szymkovisk, A.E., Dopita M.A., Mathewson, D.S. and Culhane J.L. 1982, *Ap.J.*, **255**, 440.

Dopita, M.A. and Touhy, I.R. 1984, *Ap.J.*, **282**, 135.

Kirshner, R.P., Morse, J.A., Winkler, P.F. and Blair W.P. 1989, *Ap.J.* **342**, 260.

Manchester, R.N. and Peterson, B.A. 1989, *Ap.J.* (Letters), **342**, L23.

Mathewson, D.S. Dopita, M.A., Tuohy, I.R. and Ford V.L. 1980, *Ap.J.* (Letters) **242**, L73.

Middleditch, J. and Pennypacker, C. 1985, *Nature*, **313**, 659.

Middleditch, J., Pennypacker, C.R. and Burns, M.S. 1987, *Ap.J.*, **315**, 142.

Nagase, F., Deeter, J., Dotani, T., Lewis, W., Makino, F. and Mitsuda, K. 1990, *Ap.J.* (Letters), **351**, L13.

Seward, F.D., Harnden, F.R. Jr. and Helfand, D.J. 1984, *Ap.J.* (Letters), **287**, L19.

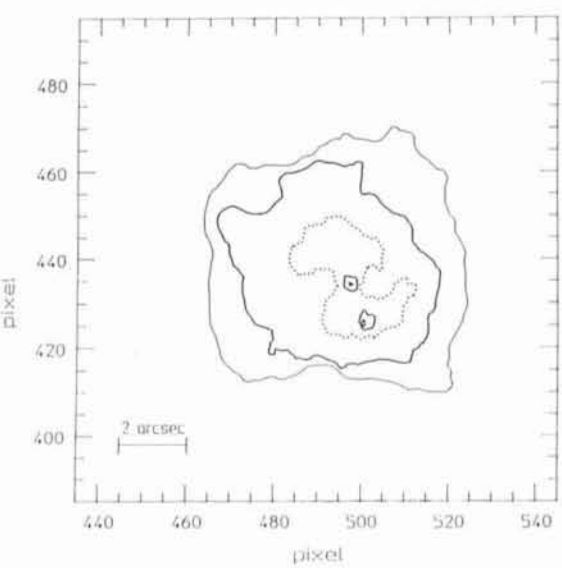


Figure 6: *Superposition of outer contours of the remnant as seen at various wavelengths. Thin line OIII, thick line V, dotted line Hα, the two continuum maxima are also shown.*