HUBBLE SPACE TELESCOPE MULTIEPOCH IMAGING OF THE PSR B0540−69 SYSTEM UNVEILS A HIGHLY DYNAMIC SYNCHROTRON NEBULA\(^1\)

A. De Luca  
INAF–Istituto di Astrofisica Spaziale e Fisica Cosmica, Via Bassini 15, I-20133 Milan, Italy; deluca@iasf-milano.inaf.it

R. P. Mignani  
Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK; rm2@mssl.ucl.ac.uk

P. A. Caraveo  
INAF–Istituto di Astrofisica Spaziale e Fisica Cosmica, Via Bassini 15, I-20133 Milan, Italy; pat@iasf-milano.inaf.it

G. F. Bignami\(^2\)  
Agenzia Spaziale Italiana, Via Liegi 26, I-00198 Rome, Italy; bignami@asi.it

ABSTRACT

PSR B0540−69 is the Crab twin in the Large Magellanic Cloud. The age and energetic and overall behavior of the two pulsars are very similar. The same is true for the general appearance of their pulsar wind nebulae (PWNe). Analysis of Hubble Space Telescope images spanning 10 yr unveiled significant variability in the PWN surrounding PSR B0540−69, with a hot spot moving at \(\sim 0.04c\). Such behavior, reminiscent of the variability observed in the Crab Nebula along the counterjet direction, may suggest an alternative scenario for the geometry of the system. The same data were used to assess the pulsar proper motion. The null displacement recorded over 10 yr allowed us to set a 3 \(\sigma\) upper limit of 290 km s\(^{-1}\) to the pulsar velocity.

Subject headings: pulsars: individual (PSR B0540−69) — stars: neutron

1. INTRODUCTION

PSR B0540−69 in the Large Magellanic Cloud (LMC) is one of the youngest pulsars known to date\(^3\) (characteristic age \(\tau \sim 1600\) yr) and one of the very few first observed at wavelengths other than radio. It was discovered in X-rays by the Einstein Observatory (Seward et al. 1984), soon detected to pulsate in the optical (Middleditch & Pennypacker 1985), but detected in radio only 10 yr later (Manchester et al. 1993).

PSR B0540−69 is a fast (\(\sim 50\) ms), classical pulsar with a rotational energy loss very similar to that of the Crab (\(\sim 1.5 \times 10^{38}\) erg s\(^{-1}\)). Thus, the detection of a polarized plerion-like structure (Chanan & Helfand 1990) came as no surprise, making it the most Crab-like of the Crab-like remnants.

With the first high-resolution optical images of the field (Caraveo et al. 1992) it was possible to identify the pulsar optical counterpart (\(V \sim 22.6\)), disentangling it from the surrounding structured plerion. This picture was confirmed by a snapshot Hubble Space Telescope (HST) observation (Caraveo et al. 1998) which clearly resolved, within \(\sim 4''\) from the pulsar, the plerion, elongated in the northeast-southwest direction.

Using early Chandra data, Gotthelf & Wang (2000) and Kaaret et al. (2001) performed a morphological study of the plerion in the X-ray band and found a noticeable similarity (accounting for different distance) with the Crab pulsar-wind nebula (PWN). Furthermore, Gotthelf & Wang (2000) unveiled the presence of a brighter PWN region southwest of the pulsar. Somehow in analogy with the Crab case, they suggested that such a region belongs to a torus around the source, since it appears perpendicular to a much fainter structure protruding from the pulsar and tentatively identified as a jet.

Caraveo et al. (2000) performed a multiwavelength analysis of the PSR B0540−69 PWN morphology by superimposing Chandra and HST images, finding a good correlation between the optical and X-ray structures with the PWN emission enhanced in both cases southwest of the pulsar, i.e., along the putative torus proposed by Gotthelf & Wang (2000).

More recently, detailed studies of the system, based on both narrow- and wide-band HST observations (Serafimovich et al. 2004; Morse et al. 2006), further strengthened the similarity with the Crab owing to the presence of a cage of filamentary ejecta possibly originating, at least in part, in a presupernova mass ejection phase (Caraveo et al. 1998). The complex interaction between the PWN and such an envelope dominates the plerion multiwavelength morphology, as confirmed by Petre et al. (2007) based on analysis of deep Chandra observations.

Interestingly, Serafimovich et al. (2004), using two HST images taken \(\sim 4\) yr apart, reported a tentative pulsar proper-motion measurement of \(4.9 \pm 2.3\) mas yr\(^{-1}\) (for a pulsar projected velocity of \(1190 \pm 560\) km s\(^{-1}\)), aligned with the putative southern jet of the PWN. This would make PSR B0540−69 the third pulsar, after the Crab (Caraveo & Mignani 1999; Ng & Romani 2006) and Vela (Caraveo et al. 2001; Dodson et al. 2003) pulsars, with a proper motion aligned with its PWN jet and, possibly, with the spin axis, which would have important consequences for pulsar kick models as well for studies of the pulsar/PWN interactions.

In this letter, we report the results of our analysis of the extended PSR B0540−69 HST archived data set, which allowed us to study possible morphological changes in the PSR B0540−69 PWN and to assess the pulsar proper motion over a longer time baseline.

2. HST DATA ANALYSIS AND RESULTS

Recent HST observations of PSR B0540−69 were performed on 2005 November 15 with the Wide Field Planetary Camera 2 (WFPC2), using the wide-band F555W (480 s) and

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\(^2\) Istituto Universitario di Studi Superiori di Pavia, Via Luino 4, 27100 Pavia, Italy.

\(^3\) See http://www.atnf.csiro.au/research/pulsar/psrcat/.
the medium-band F547M (1040 s) filters. Such data add up to WFPC2 observations collected in 1995 and 1999 with several different filters (see Morse et al. 2006 for a log of the observations). In order to study the PWN variability, as well as the pulsar proper motion, an accurate superposition of multiphoch data is required. We decided as a first step to use only the observations performed using the F555W filter, which have a better signal-to-noise ratio. Moreover, the significant WFPC2 geometric distortion, crucial for a correct proper-motion measurement, has been accurately mapped for the F555W filter (Anderson & King 2003). The selected data set, which also provides a time baseline of \( \geq 10 \) yr, includes the recent 2005 observation, as well as the original 1995 October 19 (600 s) observation (Caraveo et al. 1998).

The data were retrieved from the ST-ECF archive and reprocessed on the fly using the most appropriate reference files. Data reduction and analysis was performed using the IRAF STSDAS, MIDAS, and FTOOLS packages. Individual frames collected during each visit were combined to remove cosmic-ray hits and averaged. Residual cosmic-ray traces were removed using specific algorithms within MIDAS.

In order to register the frames, we followed the procedure we had already applied in several previous astrometric works with \( 
\text{HST}\) (see e.g., Caraveo et al. 1996, 2001; De Luca et al. 2000; Mignani et al. 2000). A relative reference frame was defined for each image, selecting a sample of good (well-resolved, not saturated, not extended, not too close to the CCD border) reference sources. In the crowded field of PSR B0540–69, 85 good sources were identified. Their position was evaluated by fitting a two-dimensional Gaussian function to their intensity profile, with a resulting uncertainty of 0.02–0.06 pixels per coordinate. The position of the pulsar optical counterpart was evaluated in the same way, with an uncertainty of order 0.03–0.04 pixels per coordinate. The coordinates of the reference stars and of the pulsar were then corrected for the WFPC2 geometric distortion using the mapping of Anderson & King (2003), as well as for the “34th row” defect (Anderson & King 1999).

Next, the 1995 reference grid was assumed as a reference and was aligned along the right ascension and declination according to the telescope roll angle. Then we computed the best plate transformation (accounting for independent shift and scale factor for each axis, as well as for rotation angle) between the two grids of reference stars. We applied an iterative clipping routine to discard reference stars yielding larger residuals. After rejecting 15 stars, we obtained a very good frame superposition, with rms uncertainties of 0.06 pixels per coordinate.

### 2.1. Proper Motion of the Pulsar

The 2005 pulsar position was translated to the 1995 reference frame to compute the pulsar displacement over the 10.1 yr time span. Such a displacement turned out to be 0.01 ± 0.09 pixels in right ascension and 0.02 ± 0.08 pixels in declination, i.e., statistically null. Using the well-calibrated WFPC2 plate scale, we set a 3 \( \sigma \) upper limit to the source proper motion of \( \sim 1.7 \) mas yr\(^{-1}\). At the known pulsar distance (51 kpc), such a limit corresponds to an upper limit to the total pulsar velocity (projected on the plane of the sky) of \( \sim 410 \) km s\(^{-1}\).

As a further check, we included in our astrometric analysis the WFPC2 observations performed through the F547M filter on 2005 November 15 and 1999 October 17 (800 s). Indeed, the F547M filter (pivot wavelength 5438 Å, \( \Delta \lambda = 483 \) Å FWHM) has a narrower bandpass than the F555W filter (pivot wavelength 5439 Å, \( \Delta \lambda = 1228 \) Å FWHM), but the pivot wavelength is essentially the same. Thus, the wavelength dependence of the geometric distortion should not induce any bias when using the correction optimized for the F555W filter. The analysis was performed as above, using the same reference stars. The superposition accuracy to the 1995 reference grid turned out to be accurate within \( \sim 0.08 \) pixels per coordinate (i.e., only slightly less accurate than for the superposition of the F555W data), with no evidence for systematic effects. Also in this case, no significant displacement was measured for the pulsar. Combining F555W and F547M data yields a tighter 3 \( \sigma \) proper-motion upper limit of 1.2 mas yr\(^{-1}\), corresponding to a projected velocity of \( \sim 290 \) km s\(^{-1}\). Such a limit, computed using a well-tested, robust algorithm, supersedes the result by Serafimovich et al. (2004), based on a much shorter time baseline.

#### 2.2. Variability of the PWN

The epoch-to-epoch coordinate transformation was then used to rebin and superimpose the images in order to search for possible variations of the PWN morphology. The resulting images were not corrected for geometric distortion. However, we note that at the PWN position, imaged at the center of the PC chip, the maximum distortion correction is \( \sim 0.05 \) pixels per coordinate (Anderson & King 2003), i.e., small enough for our goals.

As a first step, we checked the consistency of the photometry between the observations performed through the same filter at different epochs. To this aim, we compared the count rates from 85 reference stars using simple aperture photometry. The 2005 F555W observations yield systematically lower count rates, with an average 2005–to–1995 ratio of 0.86 (0.07 rms), while the 2005–to–1999 ratio for the F547M observations is 0.90 (0.08 rms). Such values were used to renormalize the 2005 images.

We started using the 1995 and 2005 F555W images, characterized by a better signal-to-noise ratio. A striking change in the brightest portion of the PWN is immediately apparent when comparing the two images. As noticed by Caraveo et al. (2000), a definite surface brightness maximum is seen in the PWN, southwest of the pulsar optical counterpart. Such a feature, which we call the “hot spot,” is resolved (7.2 pixels FWHM, or 0.081 pc at the LMC distance) and lies \( \sim 1.1'' \) away from the pulsar (0.27 pc) in the 1995 image. Inspection of the 2005 image shows that the hot spot is displaced by \( \sim 0.5'' \) in the southwest direction with respect to its location in 1995. This is apparent from Figure 1, where the two images are compared. Fitting a Gaussian function to the hot-spot profile, we estimated that the feature moved by \( 0.46'' \pm 0.02'', \) or 0.11 pc at the LMC distance, corresponding to a velocity of \( \sim 0.037c \) assuming simple linear motion. The apparent displacement of the hot spot corresponds to a very large local variation in the PWN surface brightness. Using an 8 × 8 pixel aperture (\( \sim 0.36'' \times 0.36'' \)) centered on the 1995 hot-spot position, the count rate is seen to decrease by \( 25\% \pm 2\% \) between 1995 and 2005 (the uncertainty does not account for systematic errors in image renormalization). We have computed the ratio of the 2005-to-1995 surface brightness using the same 8 × 8 pixel aperture, selecting 200 positions to cover the whole PWN (within \( \sim 2.5'' \) from the pulsar). Such an exercise proved that the region of the hot spot is by far the...
most active part of the PWN. The observed rms variability on
the above 200 PWN regions is \( \sim 8\% \), which reduces to \( \sim 4\% \)
when considering only the brightest 100 regions. Of course,
the possible systematics involved in the 2005-to-1995 renor-
malization do not affect such a conclusion.

The hot spot is clearly seen in the image collected in 2005
with the F547M filter, at a position consistent with that apparent
in the F555W filter. The ratio of the 2005 F547M and F555W
images does not show any significant feature at the hot-spot
position, which suggests that the hot-spot emission is domi-
nated by continuum. Indeed, considering a 4 pixel radius ap-
erture centered at the hot spot, we estimated the ratio of the
observed background-subtracted count rates to be \( 0.4 \pm 0.1 \).
This is fully consistent with an expected value of 0.45, eval-
uated with the WFPC2 Exposure Time Calculator,\(^4\) assuming
a power-law spectrum of spectral index \( \alpha = 1.6.\)\(^5\)

Thus, we can use the 1999 F547M image (see Fig. 1 of
Serafimovich et al. 2004) to constrain the position of the hot
spot at a third epoch. Results are shown in Figure 2. The hot-
spot peak in 1999 lies \( \sim 0.38\) arcsec west of its 1995 position,
while in 2005 it is seen \( \sim 0.33\) arcsec south of its 1999 position. The hot-spot
morphology is also seen to vary, the feature being more ex-
tended in 1999. Such results argue against simple outward
motion of the feature and prove dramatic variability of the PWN
in the southwest region.

The detection of large time variability in the PWN of PSR
B0540\(–69\) makes its similarity to the Crab Nebula even more
compelling. Thus, it seems natural to compare in some detail
the optical phenomenology of the two systems. The hot spot
in the PSR B0540\(–69\) PWN is definitely larger and more dist-

dant from the pulsar than the bright, highly variable “wisps”
seen in the Crab Nebula (Hester et al. 1995, 2002). It is some-
what reminiscent (in physical dimensions, distance to the pul-
sar, and temporal behavior) of a large, roughly arc-shaped struc-
ture in the outer Crab Nebula, first noticed in the optical by
Hester et al. (1995) because of its outstanding variability on a
timescale of 6 yr (see their Fig. 12d). Such a feature is also
prominent and highly variable at radio wavelengths (see Fig. 2
of Bietenholz et al. 2004). While the nature of such a feature
is not understood, it is almost certainly related to energy out-
flows in the counterjet channel of the Crab PWN (Bietenholz
et al. 2004). Complex interactions between the PWN and the
surrounding ejecta filaments are also seen in such a region,
roughly corresponding to the inner portion of the northeastern
“bay” (Michel et al. 1991; Hester et al. 1995). We retrieved
and inspected \( HST \) WFPC2 images of the Crab collected in
1994 and 2001 through the F547M filter. We found that the
outer feature shows a variability consistent with that reported

\(^4\) Available at http://www.stsci.edu/hst/wfpc2/software/.

\(^5\) Serafimovich et al. (2004), in their spatially resolved study of the PWN
spectrum, used a region (“area 2”) encompassing the hot spot. Emission from
such a region, largely contributed by the hot spot, is consistent with a power
law of spectral index \( 1.6 \pm 0.4 \).
by Hester et al. (1995), corresponding to a local surface brightness variation of order 25%, very similar to the hot spot of PSR B0540−69. We also note that, rescaled at the LMC distance, the variability in the inner nebula (wisps and torus) would be difficult to detect, while the variability of the outer structure would be outstanding.

Coming back to PSR B0540−69, the hot spot lies in the region of the PWN tentatively identified as an equatorial torus by Gotthelf & Wang (2000). The large variability of the feature, coupled to the PWN asymmetry with respect to the pulsar position, as well as the comparison with the case of the Crab, may point to an alternative scenario in which the northeast-southwest axis corresponds to the direction of a pulsar jet/counterjet. This may also be supported by the observation that other PWNe do show (in X-rays) the largest variability along the jet direction, with apparent complex motion of bright blobs, although on shorter timescales (e.g., for PSR B1509−58 and Vela; Delaney et al. 2006; Pavlov et al. 2003), as well as on a smaller physical scale (in Vela; Pavlov et al. 2003). However, no firm conclusions may be drawn based on current data.

3. CONCLUSIONS

With the discovery of significant variations in its PWN emission, PSR B0540−69 shares one more characteristic with the Crab pulsar. Moreover, our multiepoch study of PSR B0540−69 yielded a new assessment of the pulsar proper motion, setting an upper limit of 290 km s\(^{-1}\).

Upcoming WFPC2 observations of PSR B0540−69 will allow us to monitor the PWN morphology while lowering the measurable velocity to \(\sim 220\) km s\(^{-1}\). The new \textit{HST} data will be very important to shed light on the geometry and dynamics of the system. High-resolution \textit{HST} polarimetric mode observations, to be collected in the same program, will offer invaluable clues in order to understand the overall structure of the PWN and its complex interaction with the cage of filamentary ejecta. PSR B0540−69 will possibly become a unique extragalactic laboratory for studying and understanding the variability and evolution of young PWN systems.

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