The many faces of Gyulbudaghian's Nebula

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Gyulbudaghian's Nebula is one of a small number of nebulae that clearly changes in appearance on timescales of months or years. It is associated with the pre-main sequence star PV Cephei and can take on a range of appearances. When PV Cephei is dim, only a faint and diffuse nebulosity is visible with CCDs, but at other times it can be detected in a 0.35m telescope visually. We report on the changes within the nebula observed from 2009 July to 2015 November by members of the BAA Deep Sky Section, using a diverse range of telescopes and cameras. Most of the observations were undertaken without filters, but they have been scaled and resampled to provide indicative trends in brightness for different parts of the nebula.

Introduction

Variable nebulae are a small class of nebulae whose appearance changes significantly over astronomically short timescales of years, months or days. They have been known since the 1800s,[1] with the most familiar being Hubble's Variable Nebula (NGC 2261) in Monoceros, Hind's Nebula (NGC 1555) in Taurus and NGC 6729 in Corona Australis. In recent years the list has been added to, with McNeil's Nebula found in 2004, and the reporting of the V900 Mon Thomme's Nebula in 2011.

First recorded in 1977 by Armen Gyulbudaghian and Tigran Magkyan, Gyulbudaghian's Nebula is a bipolar nebula located in the northern hemisphere constellation of Cepheus. It is associated with the Herbig Ae/Be-type, pre-main sequence star PV Cephei, which is estimated to be of three solar masses (depending upon the distance assumed).

Gyulbudaghian's Nebula consists of a relatively dim emission nebula that is sporadically outshone by a reflection nebula component, spanning approximately 1.5×1.0arcmin, which is illuminated by PV Cephei. The nebula forms a minor part of a much larger complex of dark nebulosity, LBN 468, which is run through with thick regions of obscuring dust spanning several degrees, and which extends nearly as far as NGC 7023. If the distance to PV Cephei is assumed to be around 343pc,[2] lower than that quoted in some older Gyulbudaghian-associated publications, the visible part of the nebula extends to less than one light-year north of PV Cephei.

PV Cephei possesses an unevenly populated active accretion disk which gives rise to a substantial polar outflow of high-velocity gas and dust. This is aligned north and south of PV Cephei, with the axis tilted slightly towards us out of the plane of the sky: we are therefore looking into a cone, partially cleared by the north polar flow. The apparent tilt of the northern fan to the west probably results from local gas cloud conditions; the dimmer opposite cone projects south into the dust cloud where it suffers considerable extinction – beyond the 5–7 magnitudes already experienced by PV Cephei.[3]

The Byurakan Astrophysical Observatory study which led to the discovery of Gyulbudaghian's Nebula was on Herbig–Haro (HH) objects, including the small HH 215,[4] which lies a few arcseconds north of PV Cephei and thus within the larger reflection nebula. HH 315/HH 415 lie close by. It is normally assumed that these more remote HH objects are associated with PV Cephei and their positions have been the subject of considerable discussion.[5]

The reflection nebula has been seen to change in both appearance and brightness over a variety of timescales, both long and short. However, on occasions it may appear essentially absent for months. During bright episodes it is visible visually with telescopes of 0.357m aperture and larger but, during dim periods; it is at best faintly visible even when using CCDs. It is reported as always visible in the I-band.[3] The combination of optical dimness and extended periods of inactivity may account for its relatively late date of discovery. During the period of our study, the

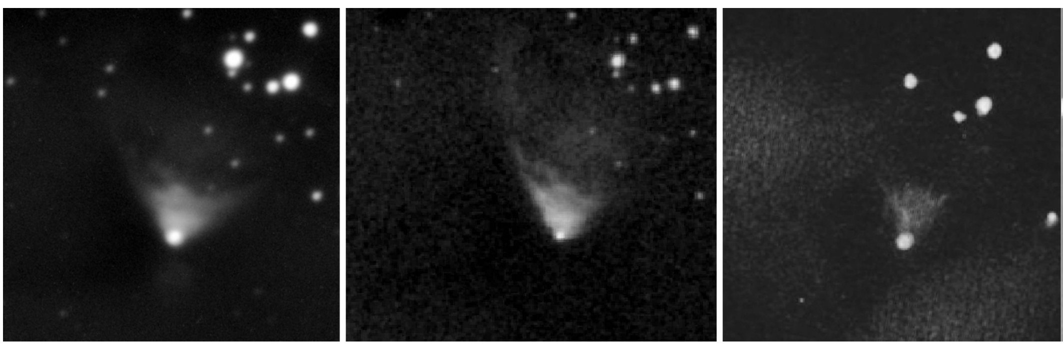

Figure 1. Three views of Gyulbudaghian's Nebula. *Left*: the sum of images reported herein. *Middle*: data from the B-band ESO Digital Sky Survey. *Right*: a drawing by Dale Holt of a Watec image obtained using a 505mm Newtonian.

star remained visible with amateur equipment, even when the nebula was not.

The project

Before the arrival of automated CCD imaging, long-term observations of Gyulbudaghian's Nebula were rare, with only a handful of teams working on it and for relatively short periods of time. Today's greater availability of affordable telescopes and CCDs has meant that useful observations are now achievable by amateurs,[6] and a better appreciation of the variations in brightness and phenomenology of both PV Cephei and the nebula is being gleaned.

To support this aim, in 2007 the BAA Deep Sky Section began requesting that active observers take regular images of the nebula and submit them as FITS files to the Section for coordinated analysis.[7] In addition, starting in 2010 and partly funded by the BAA, images were to be collected semi-regularly *via* the 0.6m Sierra Stars Observatory Network (SSON) telescope (now iTelescope T24).

The intent was to process those images received, to estimate the brightness of the star PV Cephei and to note how the brightness and appearance of the nebula changed over time. The project in that form ran for six years and this paper constitutes a report of some of the results from the period 2009 July to 2015 November.

During the early part of our activity, BAA member David Boyd began an independent study during which he concluded that the R-band brightness of the star and nebula appeared to vary similarly, but with a time lag.[8] He postulated a model where the difference in the light travel time between PV Cephei and us, and that of light travelling from the star to a portion of the nebula and then reflected toward us, leads to similar, but offset light curves. This approach gave good results over the data at that time. It is worth noting that, in a striking coincidence, the brightness of Gyulbudaghian's Nebula in the R and J-bands has been observed to be offset by a period – 30 days – that is not dissimilar to that derived by Boyd, of 28 days.[3] A further report by Boyd is currently in preparation,[9] which may highlight differences between our broadband observations and his R-band images.

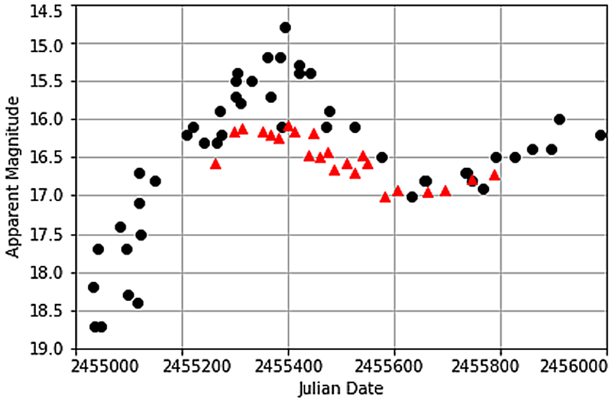

Figure 2. A comparison of broadband magnitude results for PV Cephei from multiple observers (various symbols) versus R-band filtered observations (red triangles) from ref. 8.

Table 1. Observers & equipment

Observer	*Instrument aperture (m)*	*Filter*	*Camera*
Andrea Tasselli	0.6	V/R/I	FLI Proline PL09000
Andrew Luck	0.3	Clear	FLI IMG1024
Bob Garner	0.35		SBIG ST2000XM
Dale Holt	0.55	Clear	Watec 120N & Vidcamx0.5
Daniel Self	0.5	RGB	Canon 350D
Owen Brazell	0.6	Clear	FLI Proline PL09000
Mike Harlow	0.3	Clear	Starlight MX916
Steven Goldsmith	0.3	G	ATIK 16IC-S
Geoff Thurston	0.23	Clear	ATIK 314L
Grant Privett	0.6	Clear	FLI Proline PL09000
	0.25	Clear	Starlight MX7

Observations

The observations reported herein were undertaken by observers using a variety of equipment, given in Table 1.

Over the period of data collection the number of contributing observers gradually diminished, until after 2013 it was constrained to Garner, Harlow and Privett. The sequence of SSON observations stopped at the start of 2016, when the BAA Deep Sky Section Variable Nebula Coordinator was unable to continue due to personal commitments. Prior to that, the SSON data were collected at 6–8 week intervals, with two longer delays caused by issues with telescope pointing, tracking errors, CCD flaws, poor focus, bad weather, local wildfires and – occasionally – telescope tasking mistakes.

Most of the images captured were unfiltered for maximum sensitivity; therefore the magnitude values derived from them are not photometrically accurate. However, for the purposes of seeing overall brightness trends, most unfiltered CCDs and also the G-band of DSLR images can be taken to crudely approximate the Johnson-Cousins V-band, with an offset specific to the system used. The translation is not reliable and no better than 0.5-magnitude accuracy is generally possible, especially if the colour of the source is changing or the source has a low signal-to-noise ratio.

Photometric solutions were derived for each image using the *Hubble Guide Star Catalogue V1.1* (GSC) and the *AstroArt 5/6/7* software, with considerable care taken to ensure saturated or nearly saturated stars were not employed. A standard aperture photometry approach was utilised, with a slight southern bias to try to minimise influence of results by light from the northern nebula fan. Figure 2 shows how our broadband observations differed from the R-band filtered observations of Boyd, during the early part of the project.

Given the typical response of CCDs used by amateurs, the images approximated a broadband response centred on the G-band, or slightly toward the red. This led to the dilution of any strongly coloured features, but it did make it easier to determine when the nebula was present at low-activity levels.

Astrometric reduction was undertaken *via* the *astrometry.net* website,[10] to ensure the results were of consistent accuracy and that

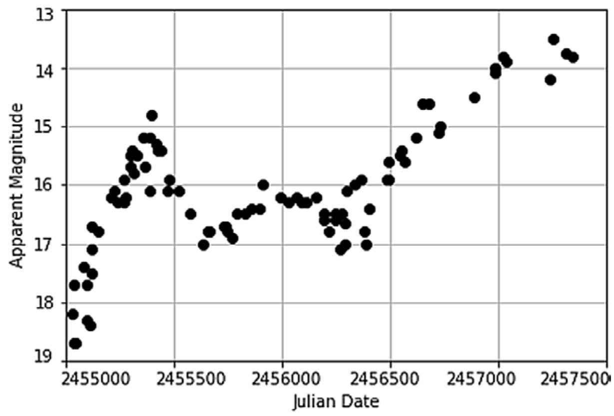

Figure 3. Variation in brightness of PV Cephei over the period covered by the project.

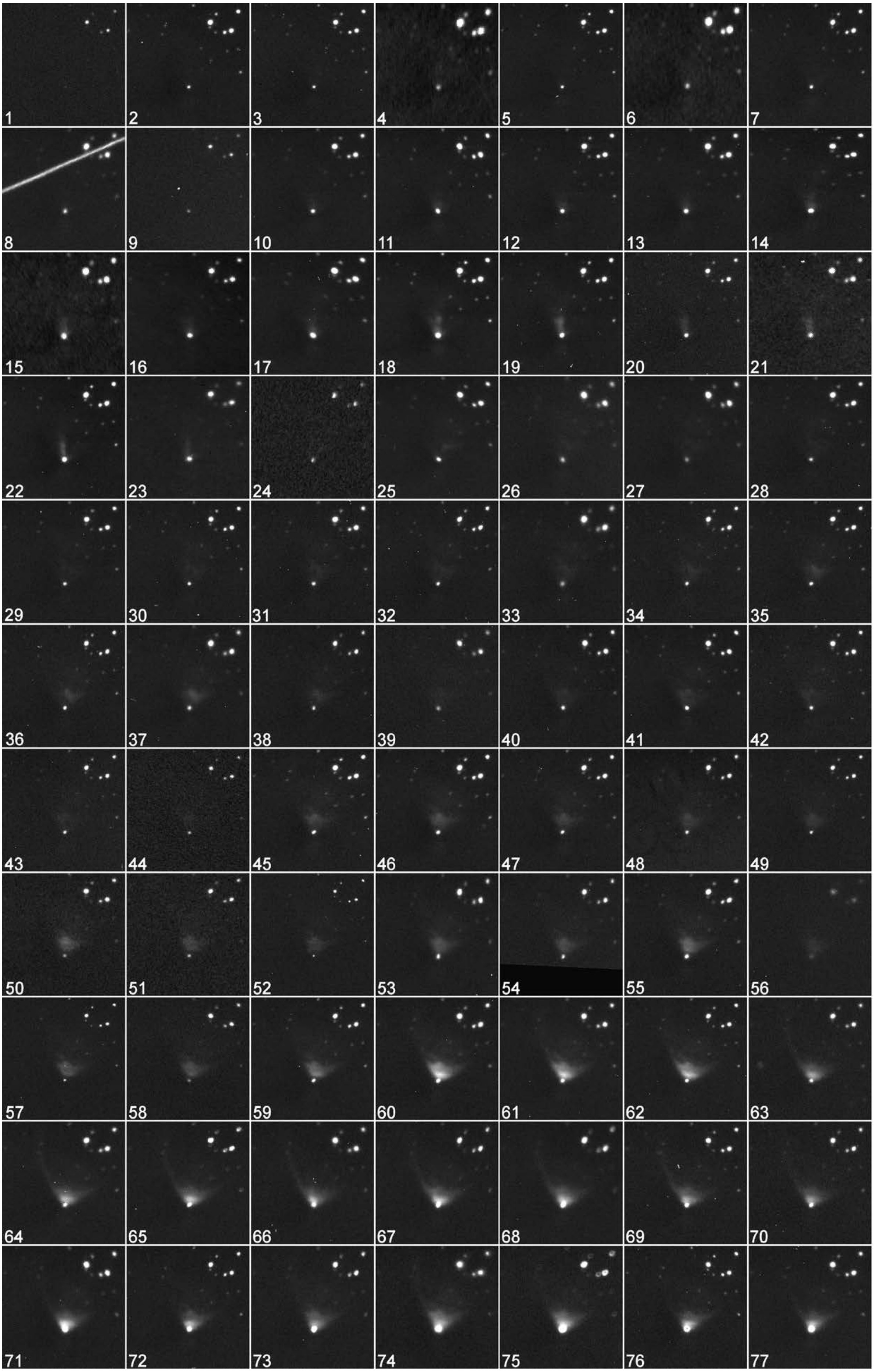

Figure 4. Montage of all imagery used in this study, with a consistent linear autoscaling applied. The date associated with each image may be found in Appendix I.

the WCS components inserted into the FITS files were compatible with exploitation using the *Python AstroPy* software library.[11]

Results

PV Cephei brightness

A light curve obtained *via* aperture photometry is presented in Figure 3. It shows the star brightening from an initial, barely detectable magnitude +18 to +19 (no nebula apparent) to +13.5 at peak. When compared with the Boyd-reported R-band brightness values, they differed most when the nebula was bright, possibly indicating a significant colour change taking place. It is reported that in mid-2008 the brightness varied between 18.5 & 17.5mag (V) following a previous bright episode in early 2008 during which the western side of the nebula fan was strongly illuminated.[12]

Unfortunately, the results reported herein were collected using images obtained at intervals that make it impossible to detect the rapid brightness variations observed by Boyd.

Nebula brightness

To aid the analysis of the nebula data, the astrometric solutions provided by *astrometry.net* were exploited *via* bespoke *Python 3* scripts to drape the data onto a common on-sky grid of 0.4arcsec spacing.

Qualitatively, it was apparent that the nebula went through a number of discrete stages and forms, which are described in Table 2.

An attempt was made to measure the brightness variation (Δ magnitude) of locations within Gyulbudaghian's Nebula, relative to unvarying parts of the nearby nebula.

The median count value present in each pixel within an area of the background nebulosity away from Gyulbudaghian's Nebula was measured, to provide a reference count. This allowed measurements from all the images to be scaled similarly. To ensure that the brightness estimates of the images were consistent, the following measurements were made for every image/date (t).

Table 2. Variation in appearance of Gyulbudaghian's Nebula during the project

Dates	*Appearance*
2009 Jul – 2010 Mar	The northern fan remains as dim as the southern fan. PV Cephei very dim.
2010 Mar – 2010 Aug	The northern part of the fan closest to PV Cephei starts to brighten and a bright narrow column appears orientated slightly north-east of PV Cephei. Running about 30arcsec, on some occasions it appears to have two distinct components of similar brightness.
2010 Aug – 2011 Apr	The column fades and vanishes, followed by minor activity.
2011 Apr –2012 Sep	A triangular area appears to the west of the columns seen earlier and starts to brighten, followed by the fan area to the east of the column. It all becomes significantly brighter than the southern fan.
2012 Sep –2013 Jul	The fan remains brighter than it was previously, with some fluctuation and an irregular edge to the north.
2013 Jul –2014 Aug	The nebula brightens considerably, the east and west edges of the fan becoming more pronounced and forming extended wings. More detail is evident within the nebula – in particular to the east of the end of the column seen earlier. PV Cephei now at its brightest.
2014 Aug – 2015 Nov	The sweeping winged edges of the nebula fade and become less distinct, but the central portion of the fan remains bright.

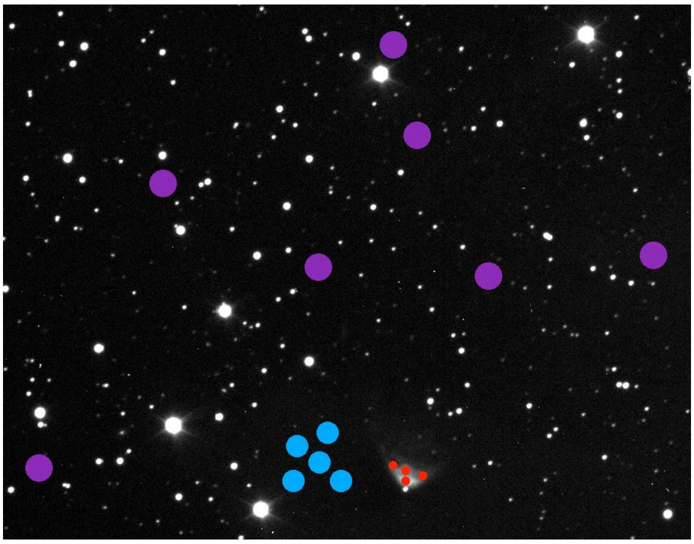

Figure 5. The locations sampled on each image, where *red*= Loc; *blue*= Neb; *magenta*= Sky. Gyulbudaghian's Nebula is under the red circles. North is up.

- Seven image locations (30×30arcsec wide) away from either the background nebula or Gyulbudaghian's Nebula were sampled to provide a median filtered sky signal estimate: Sky(t).
- Five image locations (25×25arcsec wide) within the nearby emission nebulae, but outside of Gyulbudaghian's Nebula, were sampled to provide reference nebulosity count measurements. These were median-combined: Neb(t).
- Image locations of interest (10×10arcsec wide) within Gyulbudaghian's Nebula were sampled: Loc(t).

The brightness estimates for the location in Gyulbudaghian's Nebula were then determined by:

$$\text{Brightness}(t) = 2.5 \log((\text{Loc}(t) - \text{Sky}(t)) / (\text{Neb}(t) - \text{Sky}(t)))$$

As can be seen, the sky-subtracted Neb(t) samples provide a scaling factor derived from in-scene information on each image. This allows a comparable linear stretch to be applied to all the images and hence the creation of the image montage shown in Figure 4 – for the associated image dates, see Appendix I. The scaling is not perfect, but it is less arbitrary than a manual approach.

The calculation also generates relative brightness values for different parts of Gyulbudaghian that can be plotted as a function of observation date/time. The scaling factor works best with well-exposed imagery, so some images were rejected because they were too poorly exposed to allow accurate scaling factors to be determined. Vignetting, another possible source of error, was not found to be present in the portion of the images exploited. Efforts were made to statistically mitigate the impact of noise on the image sample values derived, but no processing techniques to specifically remove cosmic rays or hot pixels were applied to the draped images. All image sampling was on a nearest-neighbour pixel basis to maximise photometric accuracy.

Table 3 contains the locations used to provide 'Sky' measurements, unvarying nebula estimates 'Neb' and the locations within Gyulbudaghian's Nebula that were sampled, 'Loc'. For convenience, they are also shown within Figure 5.

As can be seen from Figure 6, the brightness of another area of nebulosity within the field of view, that is not believed to

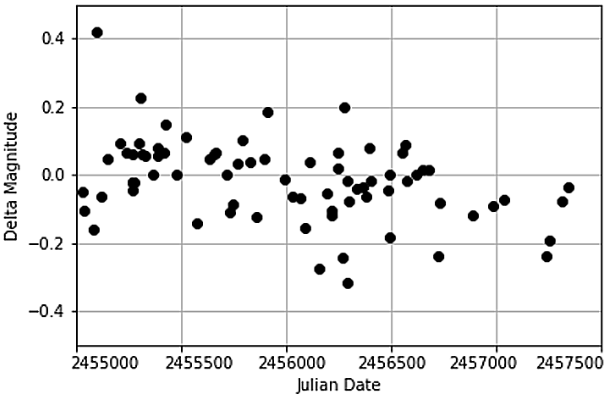

Figure 6. A plot of the brightness of a separate area of in-scene nebulosity, showing a typical variation of less than 0.5mag.

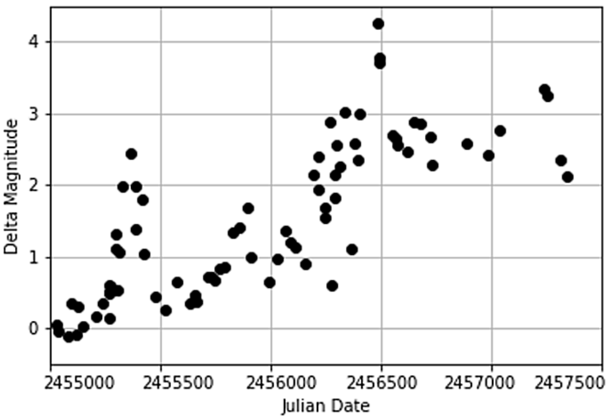

Figure 7. The brightness variation associated with a location 20arcsec north of PV Cephei.

vary in luminosity, appeared to vary by less than 0.5 magnitudes. Some noise was evident in the measurements for this comparison field, much of which probably arises from the small sample sizes employed and the significantly underexposed imagery.

For two areas to the immediate north of PV Cephei and regions of each wing of Gyulbudaghian's Nebula, there was a distinct, if noisy, upward trend of 2–5 magnitudes. The trends found for all these locations can be seen in Figures 7–10. The southern fan brightness (Figure 11) shows no obvious trend.

Unfortunately, the low frequency and sporadic observational cadence, combined with high noise levels, prevented the calculation of a delay offset between the variations of PV Cephei and the nebula.

It might be expected that the portions of nebula closest to PV Cephei would most closely follow the star's brightness variations, as the time taken for light to travel to the nebula and then to us would only be slightly longer than that taken by light travelling to us directly from PV Cephei. Similarly, it might also be expected that the parts of the nebula most remote from PV Cephei – lying some light-months away – would become illuminated only after the inner portions. This would lead to the variations shown in Figures 7 & 8 being similar, but out of phase. Unfortunately, the data does not have sufficient resolution for this to be recorded. Higher cadence imaging with a larger instrument might support such a study.

Conclusions

An indicative unfiltered light curve for PV Cephei has been created using a sequence of observations spanning the period 2009 July – 2015 November. The brightness range was found to be between magnitudes +13.4 & +18.5. During the period studied, an initial strong brightness increase was followed by an equally rapid partial fall (in accordance with ref. 8) and then a slower, longer term rise toward a later peak.

Over the same period, the nebula was seen to pass through a number of distinct forms, the sequence of which has been described. Examination of online imagery indicates that the western wing can appear brighter than we saw, while the east wing can appear thinner and longer than was observed during this project. Otherwise, it is believed most common forms taken by the nebula have been captured.

During the same period, four separate locations within the nebula were seen to vary in brightness in a manner that was generally in-step with the observations of PV Cephei. A change in brightness of between two and five magnitudes was observed during the period covered.

The fainter southern fan of Gyulbudaghian's Nebula was not seen to vary significantly.

There is a need to continue observation of this object over a longer period and with a higher cadence, to determine whether these results are typical of the behaviour of the system and to look for longer term trends.

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Table 3. Sampling locations

'Sky' sample no.	*R. A. (°)*	*Dec. (°)*	*'Neb' sample no.*	*R. A. (°)*	*Dec. (°)*	*'Loc' Nebula sample*	*R. A. (°)*	*Dec. (°)*
1	311.6154	68.0775	1	311.5341	67.9774	North of PV	311.4761	67.9664
2	311.5727	68.0945	2	311.5633	67.9743	North of PV	311.4763	67.9634
3	311.6625	68.0244	3	311.5654	67.9654	West Wing	311.4855	67.9677
4	311.5163	68.0293	4	311.5451	67.9689	East Wing	311.4547	67.9660
5	311.4251	68.0457	5	311.5330	67.9629	Southern Fan	311.4760	67.9541
6	311.8307	68.0375	–	–	–	–	–	–
7	311.4918	67.9660	–	–	–	–	–	–

Key: 'Sky' = background count. 'Neb' = calibration/scaling nebulosity count. 'Loc' = locations of interest within Gyulbudaghian's Nebula.

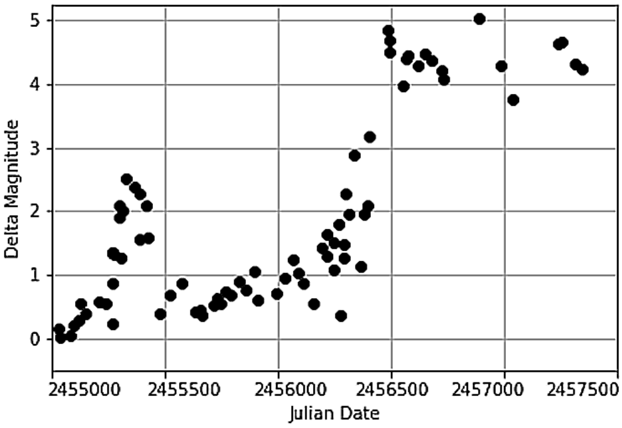

Figure 8. The brightness variation associated with a location 10arcsec north of PV Cephei.

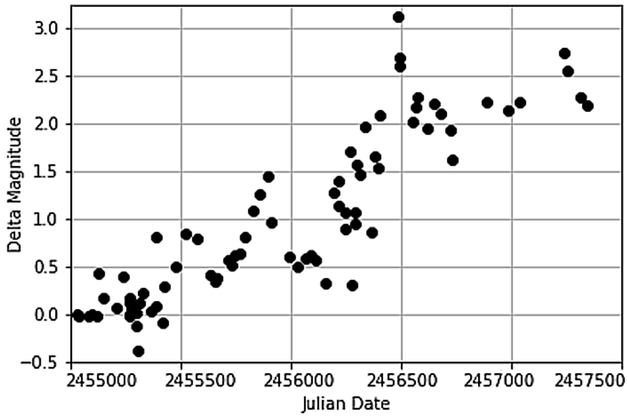

Figure 9. The brightness variation associated with the west wing of Gyulbudaghian's Nebula.

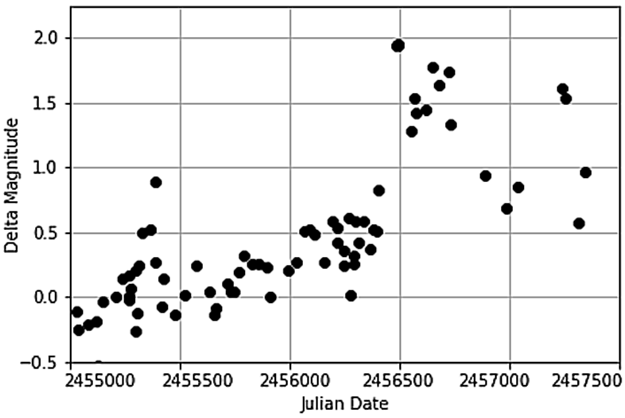

Figure 10. The brightness variation associated with the east wing of Gyulbudaghian's Nebula.

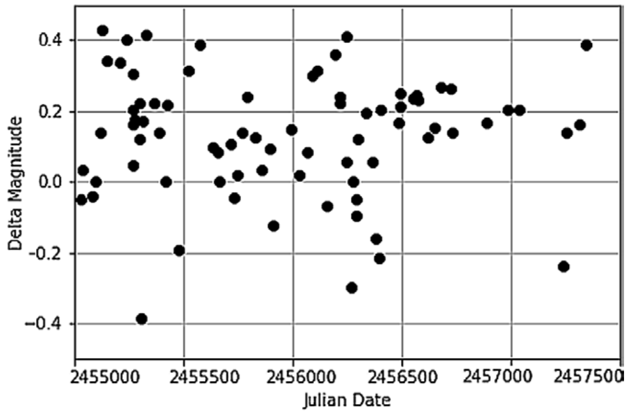

Figure 11. The brightness variation associated with the southern fan of Gyulbudaghian's Nebula.

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Table 4. Image dates

Image no.	*Date (y, mth, d)*	*Image no.*	*Date (y, mth, d)*	*Image no.*	*Date (y, mth, d)*	*Image no.*	*Date (y, mth, d)*
1	2009 07 20	21	2010 07 10	41	2012 05 20	61	2013 07 17
2	2009 07 28	22	2010 08 12	42	2012 06 13	62	2013 07 19
3	2009 09 09	23	2010 08 14	43	2012 07 04	63	2013 09 18
4	2009 09 20	24	2010 10 07	44	2012 08 19	64	2013 10 01
5	2009 10 16	25	2010 11 25	45	2012 09 23	65	2013 10 11
6	2009 10 18	26	2011 01 14	46	2012 10 16	66	2013 11 23
7	2009 11 15	27	2011 03 12	47	2012 10 16	67	2013 12 26
8	2010 01 14	28	2011 04 06	48	2012 11 13	68	2014 01 20
9	2010 02 13	29	2011 04 10	49	2012 11 14	69	2014 03 07
10	2010 03 11	30	2011 06 03	50	2012 12 10	70	2014 03 15
11	2010 03 14	31	2011 06 23	51	2012 12 27	71	2014 08 22
12	2010 03 15	32	2011 07 05	52	2013 01 02	72	2014 11 25
13	2010 03 18	33	2011 07 26	53	2013 01 04	73	2015 01 14
14	2010 04 14	34	2011 08 18	54	2013 01 20	74	2015 08 07
15	2010 04 15	35	2011 09 24	55	2013 02 14	75	2015 08 23
16	2010 04 19	36	2011 10 26	56	2013 03 14	76	2015 10 21
17	2010 04 24	37	2011 12 02	57	2013 04 01	77	2015 11 17
18	2010 05 14	38	2011 12 14	58	2013 04 11	–	–
19	2010 06 21	39	2012 03 03	59	2013 04 22	–	–
20	2010 07 09	40	2012 04 16	60	2013 07 12	–	–

Appendix I

The dates associated with the images in Figure 4 are shown in Table 4.

For reference, the Julian dates associated with the start of each year during the project are shown below.

Date	*Julian Date*
2010 01 01	2455197.5
2011 01 01	2455562.5
2012 01 01	2455927.5
2013 01 01	2456293.5
2014 01 01	2456658.5
2015 01 01	2457023.5
2016 01 01	2457388.5

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