BAV Journal

2026 No. 110 ISSN 2366-6706

Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e.V.

http://bav-astro.de

On the variability of the two reflection nebulae associated with VY Mon

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Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e.V.

July 2026

Abstract:

We present a study of the optical variability of two isolated reflection nebulae associated with VY Mon. The brighter eastern nebula is identified as HBC 522, while the fainter northern nebula is designated StraBe 4. Both nebulae show pronounced brightness variations that appear to be linked, albeit in a complex way, to the variability of VY Mon.

Introduction

Reflection nebulae are interstellar dust clouds that shine by scattering the light of nearby stars rather than by producing their own radiation [1]. While many reflection nebulae were long assumed to be optically constant, a small subset is known to exhibit pronounced brightness and morphological changes on timescales ranging from days to months. Classical examples include Hubble's and Hind's variable nebulae [2, 3]. The observed variability is generally attributed to intrinsic variations of the illuminating source and/or time-dependent shadowing effects caused by circumstellar dust structures.

Recently, we reported rapid optical variability in the reflection nebula vdB 24 ("StraBe 1") surrounding XY Per, including apparent light-echo-like structures evolving on timescales of only a few days [4]. Extending this approach to other young variable stars, we subsequently identified variable reflection nebulae around V1818 Ori ("StraBe 2") and NSV 16694 ("StraBe 3") [5]. Furthermore, we investigated light-echo effects in the reflection nebula van den Bergh 27 surrounding RY Tau [6]. Taken together, these findings suggest that time-dependent illumination effects in circumstellar environments may be more common than previously assumed.

In this paper, we analyse the optical variability of VY Mon itself and of two compact, isolated reflection nebulae located east and north of the star. We distinguish these two variable nebular features, HBC 522 and the newly designated StraBe 4, from the more extended reflection nebula IC 446 with which they are associated. The variability of the two nebulae was identified and investigated using the same observational approach that we applied to our previously studied objects. While this variability initially became apparent through our analysis of multi-epoch imaging data, a subsequent review of the literature revealed that the brighter reflection nebula located east of VY Mon is already known as the variable reflection nebula HBC 522, first reported by Paolo Maffei [7]. In his original study, Maffei described a small nebulosity of approximately 14″ in diameter, very likely associated with IC 446, which appeared variable on blue plates. He further noted that the nebulosity reached its maximum brightness during phases when VY Mon itself, located only about 20″ away, was bright, exhibiting variations similar to those of the star, although shifted in phase by several days. Although it was later included in the Herbig & Bell Catalogue as HBC 522, both modern observations and 2MASS data indicate that the object appears not to be a separate star, but rather a bright reflection knot or dust condensation illuminated by VY Mon [8].

The isolated reflection nebula located north of VY Mon has apparently neither been designated as a separate object nor, to the best of our knowledge, described as variable. We therefore assign it the designation StraBe 4 as part of our series of variable reflection nebulae. Overall, the reflection nebulae surrounding VY Mon have remained comparatively little studied in a time-resolved context, which is the main motivation for the present detailed study.

Observation and data analysis

As part of our systematic survey, we investigated the variability of the reflection nebula in the vicinity of VY Mon using the procedure described in BAVJ 104 [4]. As an initial step, candidate reflection nebulae were selected from the CCD Guide catalogue compiled by the Astronomical Working Group Salzkammergut[1]. Archival images from the Digitized Sky Surveys[2] (DSS1 and DSS2) were then retrieved and directly compared, allowing us to identify changes in brightness and apparent morphology in the vicinity of the illuminating star. This comparison provided clear evidence for optical variability in the nebulae surrounding VY Mon. An animated sequence of the DSS b-band images is available at Zenodo:
https://zenodo.org/records/21325915

For a more detailed analysis of the brightness behaviour of VY Mon, we examined imaging data obtained with the Zwicky Transient Facility, which has been conducting a systematic time-domain survey at Palomar Observatory since 2017. The ZTF camera, featuring e2v CCD231-C6 devices, is mounted on the Samuel Oschin Schmidt Telescope. Covering three passbands (g, r, and partially i), it reaches a limiting magnitude of about 20.5 mag, making ZTF data highly suitable for investigations of variable objects [9–11].

Results

According to the International Variable Star Index (VSX), VY Mon is classified as a UX Orionis-type star, a subgroup of young stellar objects known for irregular brightness variations with amplitudes ranging from barely detectable changes to more than 4 mag in V. The brightness range of VY Mon is listed in the VSX as 12.8 mag at maximum in the V band and 17.4 mag at minimum in photographic magnitude, based on AAVSO data. Using the Gaia DR3 parallax (3.1710±0.4154 mas) as a distance proxy yields a nominal distance of ~315 pc, corresponding to about 1,030 light-years. Two overview images with different levels of detail are presented in Figures 1 and 2. Figure 1, (Bernhard Hubl | CCD-Guide), illustrates the broader surroundings of the reflection nebula IC 446 associated with VY Mon. The arrow marks the position of the young variable star VY Mon. A more detailed view of the region is shown in Figure 2.

[1] https://ccdguide.com
[2] https://skyserver.sdss.org/dr5/en/proj/advanced/skysurveys/poss.asp

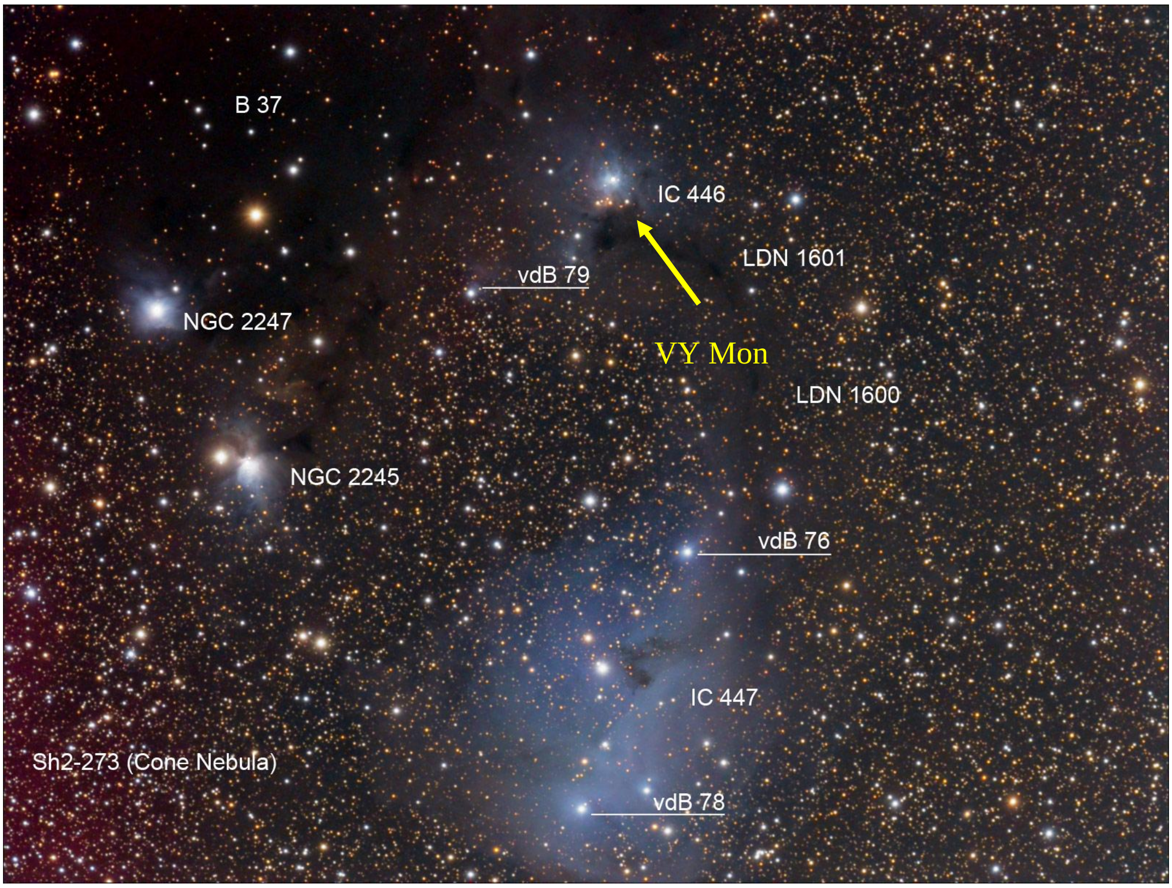

Figure 1: Overview of the field of VY Mon (Bernhard Hubl | CCD-Guide, North: up, East: left)

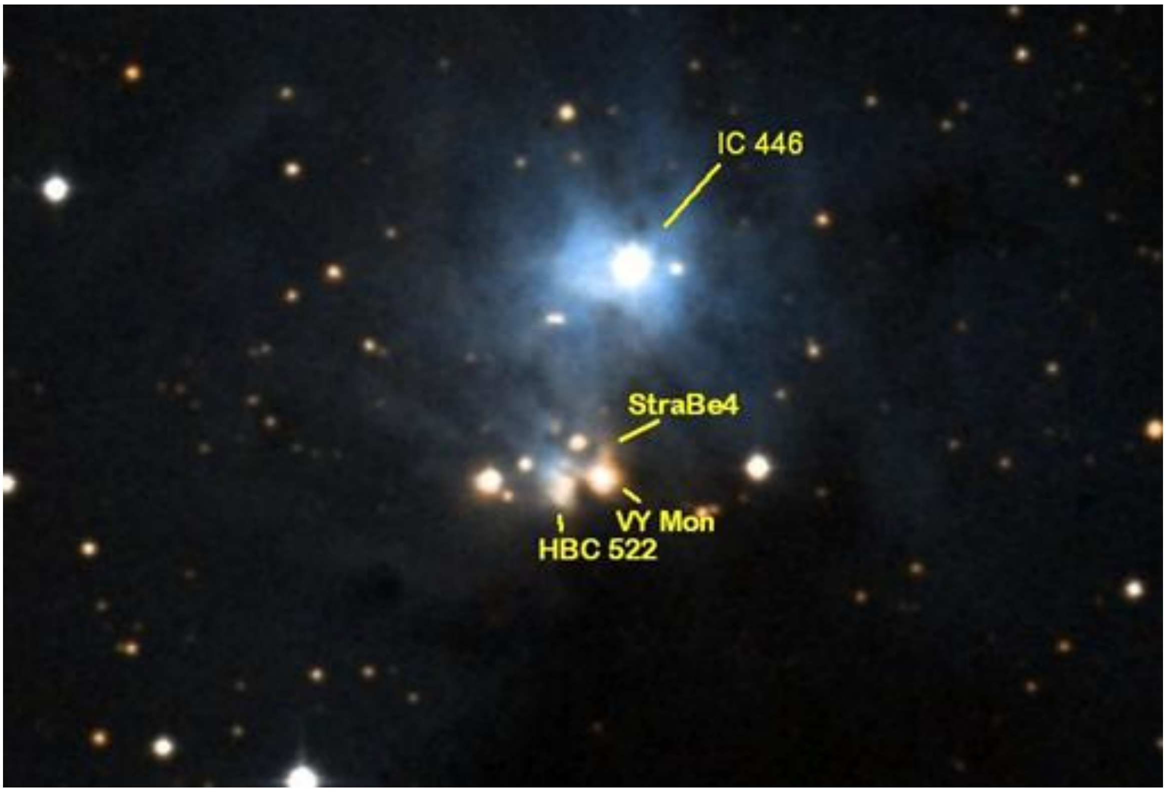

Figure 2: Detailed view of the surroundings of VY Mon in a DSS colour image based on a DSS2 colour composite retrieved with Aladin [12]. North is up and east is to the left; the field of view is about 6′ × 4′. HBC 522 is located to the left of VY Mon, while StraBe 4 lies above it.

The essential data of VY Mon are listed in Table 1:

Table 1: Essential data of VY Mon

AAVSO VSX [13]:	Variability type	UXOR (subgroup of young variable stars)
	Identifiers	ASAS J063107+1026.1, IRAS 06283+1028
	Magnitude Range	12.8 V - 17.4 p (range from AAVSO data)
Gaia DR3 [14]:	Gaia DR3 3327886213092092800	
	Right Ascension (J2000)	06 31 06.9271*
	Declination (J2000)	+10 26 04.9523*
	Plx	3.1710±0.4154 mas
	Gmag	13.96 mag

* All coordinates are taken from the Gaia DR3 catalogue (http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=I/355). The coordinates (epoch J2000) are computed by VizieR and are not part of the original data from Gaia (note that the coordinates are computed from the positions and the proper motions).

Variability of the central star

Figure 3 presents the ZTF survey zg and zr light curves of VY Mon. They reveal an obviously predominantly irregular variability on timescales of the order of months to years.

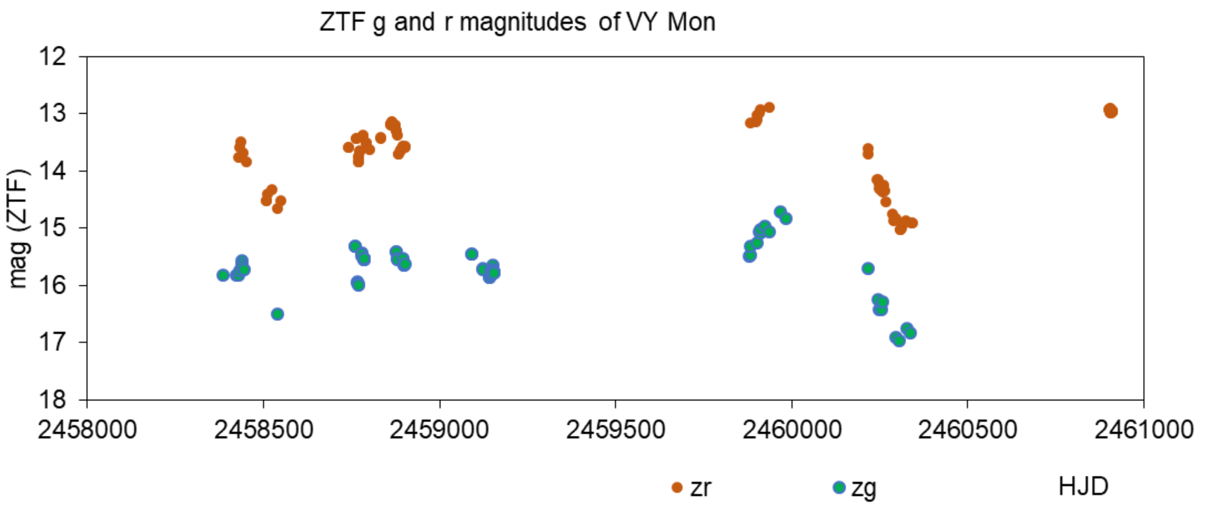

Figure 3: ZTF zg (blue) and zr (red) light curve of VY Mon between 2018 and 2025

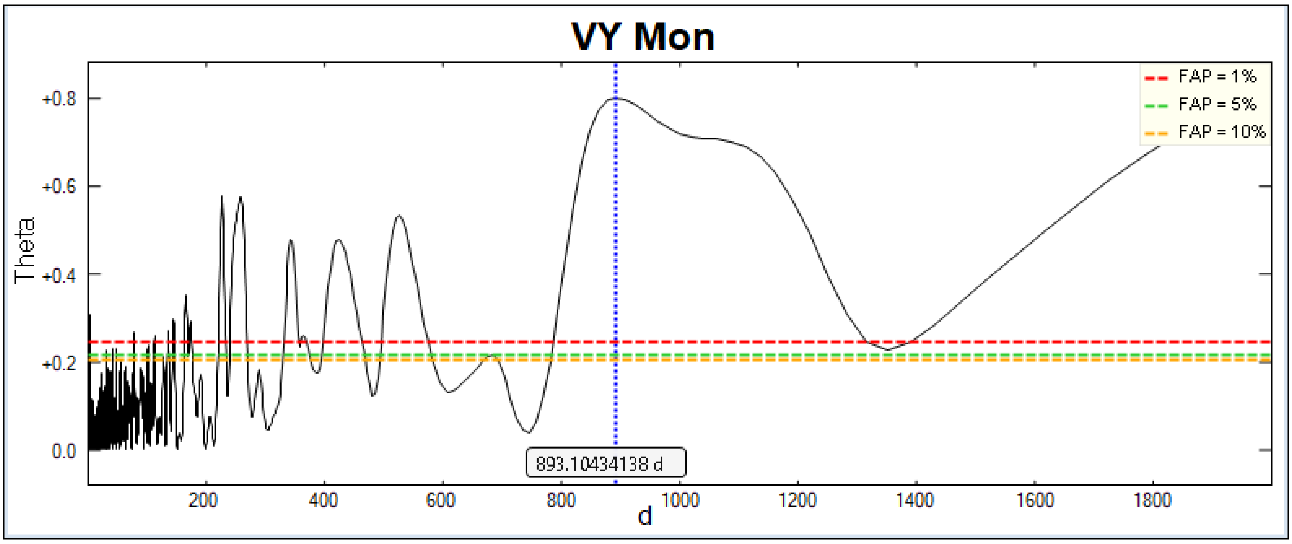

Figure 4: Peranso GLS Periodogram of the ZTF zr data

A period analysis of the ZTF (z_r) data was performed using the generalized Lomb–Scargle (GLS) method implemented in Peranso [15]. This method is particularly suitable for unevenly sampled time-series data. Prior to the analysis, only obvious outliers were removed, while no detrending was applied. In the GLS periodograms, the test statistic (Theta) represents the normalized signal power as defined in Peranso. The periodogram shown in Figure 4 displays a forest of partly broad peaks in the ZTF data, similar to what we already observed in the detailed analyses of our previously studied objects. This suggests that the detected signals most likely represent transient periodicities or irregular variability patterns rather than stable long-term periods. In particular, the visually prominent peak near 893.1 d should not be interpreted as a securely established period or ephemeris. Accordingly, the variability appears to be predominantly irregular, but with a sufficient amplitude of at least 2.0 mag to explain the optical variability of the surrounding reflection nebulae.

Variability of the nebulae (ZTF frames)

To further investigate the variability of the reflection nebulae, we downloaded ZTF images via the IRSA server. We created an animation composed of approximately 60 individual frames from the Zwicky Transient Facility (ZTF), covering the period from 2018 to 2025. For this animation, the frames in the zr band were used, as the reflection nebula is significantly more prominent in this band than in zg. The time intervals between individual images are not uniform: https://zenodo.org/records/19349887

The accompanying movie provides a useful time-resolved visualisation of these variations. Obvious slow variations in the brightness of the two nebulae are evident throughout the entire observing period. These slow brightness changes are also evident in individual images obtained at different epochs (Figure 5). While HBC 522 appears brighter in the image from 18 November 2022 than on 25 October 2023, the opposite behaviour is observed for StraBe 4.

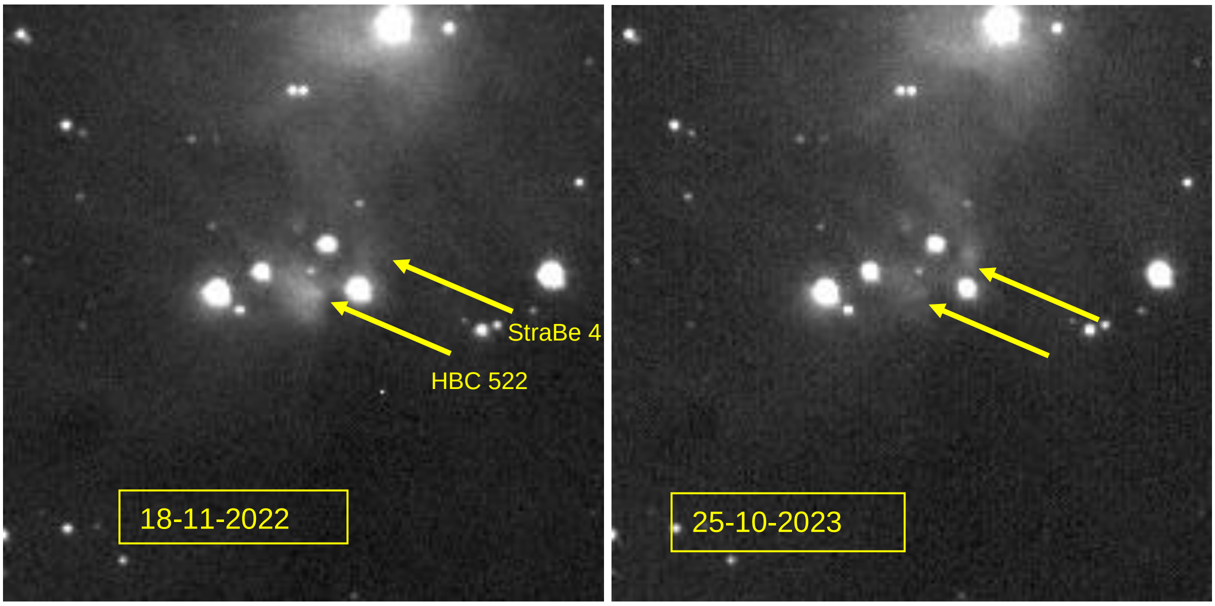

Figure 5: Example illustrating the slow variability in brightness of HBC 522 (left of VY Mon) and StraBe 4 (top of VY Mon) between 18 November 2022 (HJD 2459901) and 25 October 2023 (HJD 2460242), ZTF-r images

Although the two reflection nebulae are relatively compact and sufficiently well separated from VY Mon, they are clearly nebulous in appearance. Therefore, no automatic photometric measurements are provided for these objects in the ZTF catalogue photometry. However, test measurements demonstrated that their brightness can be estimated using the Aperture Photometry Tool (APT)[3], allowing approximate photometric values to be derived directly from the ZTF images and compared with the automatically measured ZTF data of the central star.

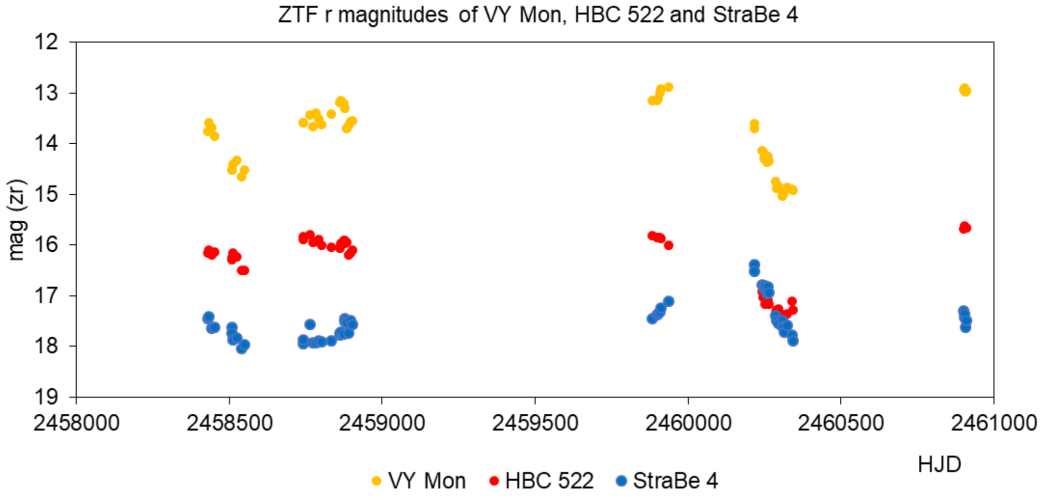

Figure 6: ZTF zr light curves of VY Mon, HBC 522 and StraBe 4 between 2018 and 2025

Figure 6 shows that the brightness of StraBe 4, which is approximately four magnitudes fainter than VY Mon, generally follows the brightness variations of VY Mon quite closely. In contrast, this behaviour is less pronounced for the brighter nebula HBC 522. This becomes particularly evident in the observations obtained between HJD 2459800 and 2460400 and is clearly reflected in the zr magnitude differences HBC 522 - VY Mon and StraBe 4 - VY Mon (Figure 7). A particularly remarkable feature is the reversal of the relative brightnesses of the two reflection nebulae between approximately HJD 2459900 and 2460200. This behaviour can also be directly verified in the corresponding ZTF images (Figure 5).

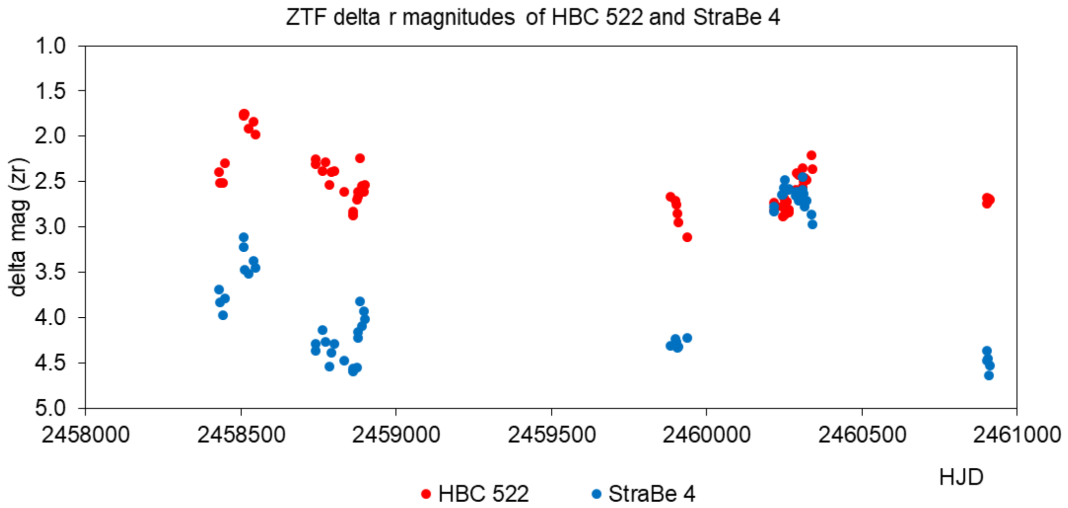

Figure 7: Delta ZTF zr light curve of HBC 522 - VY Mon and StraBe 4 - VY Mon.

To estimate the potential influence of time-delayed light-echo effects on the observed brightness variations of the reflection nebulae relative to VY Mon, the corresponding light-travel times can be approximated. Using the projected angular separations from VY Mon and the Gaia DR3 parallax

[3] https://www.aperturephotometry.org

as a distance proxy, the minimum projected light-travel times are approximately 29 d for HBC 522 and 18 d for StraBe 4.These values provide an estimate of the characteristic timescales on which brightness variations of VY Mon may be reflected in the two nebulae, although the actual delays may differ owing to the three-dimensional geometry of the scattering structures.

However, since the characteristic timescales of the variability of the central star are on the order of hundred days, it appears unlikely that the observed brightness variations are dominated by time-delayed light-echo effects. This conclusion is particularly supported by the episode between HJD 2459900 and 2460200 discussed above, but also by other sections of the light curve.

Summary and Conclusions

VY Mon and its surrounding reflection nebulae HBC 522 and StraBe 4 exhibit clearly detectable brightness variations. Although these variations are not strictly parallel, the overall behaviour of the nebular structures broadly follows that of the central star. This indicates that direct light-echo effects contribute, at least in part, to the observed variability. The characteristic timescales of the brightness changes range from several months to years. Given the projected separations of the nebulae from VY Mon, simple light-travel-time considerations suggest characteristic delays of only a few weeks. While such delays may contribute to the observed behaviour, they appear insufficient to explain all aspects of the variability, particularly the episode between HJD 2459900 and 2460200, as well as other sections of the light curves.

The remaining variability may therefore involve additional processes beyond a simple direct light-echo scenario. One possibility is that the complex distribution of circumstellar dust causes the radiation field of VY Mon to be direction-dependent, so that HBC 522 and StraBe 4 receive different illumination from that observed along our direct line of sight. Given the UXOR nature of VY Mon, variable and anisotropic obscuration by circumstellar dust may provide a plausible explanation for such direction-dependent illumination of the surrounding nebular material.

A more speculative possibility is that a fraction of the observed emission from the nebular structures is influenced by variable high-energy radiation from the central star, similar to processes commonly observed in emission nebulae. Such radiation could exhibit variability patterns that differ from those seen in the optical continuum.

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Further observations would be highly valuable for clarifying the nature of the intriguing brightness variations of HBC 522 and StraBe 4. Densely sampled time-resolved imaging, complemented by multi-wavelength observations, could help to distinguish direct light-echo effects from additional illumination or excitation mechanisms and thereby improve our understanding of the circumstellar environment of VY Mon.

Acknowledgements

This research has utilized the SIMBAD/VIZIER database and Aladin, operated at CDS, Strasbourg, France, the International Variable Star Index (VSX) database, operated at AAVSO, Cambridge, Massachusetts, USA, the Zwicky Transient Facility (ZTF) and the SAO/NASA Astrophysics Data System, USA. This research has made use of the NASA/IPAC Infrared Science Archive (IRSA), operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. This research made use of the Digitized Sky Survey, produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166, The authors thank the referees for helpful comments.

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