A dynamical study of the nova remnant of GK Per

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Abstract. Due to their large expansion speed, the apparent growth of nearby nova remnants such as GK Per can be easily resolved from ground-based optical imagery on a timescale of months. If the expansion in the plane of the sky is coupled with the Doppler shift velocities, an almost complete dynamical picture is drawn. We will discuss our latest results of such a study on GK Per.

1. Introduction

GK Per is remarkable in many aspects. It is the result of a bright classical nova explosion in 1901. For the first time in astronomy, superluminal motions were observed, and then interpreted as light echoes. The actual remnant of the explosion has turned out to be the longest lived and most energetic classical nova remnant.

2. Observations and Data Reduction

Most of the imaging data was obtained with the Isaac Newton Telescope (INT) between 2004 and 2011 using a narrow band $H\alpha+[N\,II]$ filter with a central wavelength of 6568 Å and a bandpass of 95 Å. The Wide Field Camera (WFC) with a pixel scale 0′′.33 pix$^{-1}$ was used. Occasionally, the Nordic Optical Telescope (NOT) with the Andalucía Faint Object Spectrograph and Camera (ALFOSC) with a similar filter was used. A total of 19 images, obtained with a seeing between 0′′.5 to 1′′.3, were used for the data analysis. To complement our data, five archival images were downloaded, observed between 1987 and 1999 with a different set of telescopes and filters: broad band R or narrow band $Ha$. 

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The long-slit spectra were obtained with the INT and NOT in 2007. At the INT the Intermediate Dispersion Spectrograph (IDS) was used with grating R1200Y and a 1″.5 slit covering a spectral range from 5730 Å to 7610 Å at a dispersion of 0.47 Å pix$^{-1}$. At the NOT ALFOSC with a grism #17 and 0″.5 slit was used, giving spectral range from 6350 Å to 6850 Å, and a dispersion of 0.26 Å pix$^{-1}$. Observations were secured at twelve different position angles, evenly distributed over the remnant.

All data were reduced using IRAF (see more from Liimets et al. (2012)).

3. Imaging analysis

The optical ejecta has a knotty roundish morphology (Fig. 1). However, some deviation from circular symmetry is evident. The diameter of the remnant in the northeast-southwest (NE-SW) direction is 10% smaller than in northwest-southeast (NW-SE) direction. The remnant is composed of hundreds of knots and filaments (see also Shara et al. (2012)) with different sizes and brightness. Many knots have tails pointing away or towards the central source.

Our 19 carefully registered image obtained between 2004 and 2011 allowed a precise determination of the apparent expansion of the GK Per remnant in the plane of the sky. To calculate the proper motion $\mu$ vector of individual knots the following approach was taken. First, the position of knots were measured by Gaussian fitting in the $X$ and $Y$ directions. This determines the apparent distance from the central star ($d_x$, $d_y$, and $d$). Then $\mu$ was determined by means of a least-squares fit of the positions at the different epochs, as illustrated in the Fig. [2]. This also provides the direction of the $\mu$ vector ($\alpha = \arctan(\mu_x/\mu_y)$). In this way, 282 individual knots were measured. For all them, a straight line provides an excellent fit to the variation of $d$ during the 7.9 yr lapse of time considered. Proper motion varies from 0″.007 yr$^{-1}$ to 0″.53 yr$^{-1}$. When fixing the distance to the object, $\mu$ can be transformed into velocity in the plane of the sky as follows: $v_{\text{sky}} [km \, s^{-1}] = 4.74 \cdot \mu [\farcs \, yr^{-1}] \cdot D [pc]$.

The WFC of the INT has well-defined and small geometrical distortions in the limited FOV covered by the remnant, which are robustly removed during the astrometric
registering of images. Therefore, errors in the proper motion determination mainly depend on the goodness of the fit of the position of the knots at the different epochs. The latter depends on the knots shape and brightness and their behaviour, which is rather stable. Consequently, as the proper motion error, we adopt the formal error of the least squares fit: its average value is $0''.010 \pm 0''.006$ yr$^{-1}$.

The archive images were not used for the proper motion calculations as they constitute a less homogeneous set of observations, with generally poorer resolution or astrometric properties, and different filters. The archive images were used to search for signs of acceleration/deceleration of knots in the past decade with respect to the previous 20 yr. In this respect, we found no evidence for a systematic acceleration/deceleration.

INT $H\alpha$+[N II] images were used for flux analysis. Similarly to measurements in radio (Anupama & Kantharia 2005), the total flux in optical has been linearly decreasing during the past decade with a rate of 2.6% yr$^{-1}$. However, the flux in different quadrants varies significantly. The NE quarter shows the shallowest decline and perhaps even a possible re-brightening in the past 3 yr. The SW quadrant is fading fastest.

3.1. Kinematical Ages

Kinematical ages are calculated as follows in convenient units: $t [\text{yr}] = d ["] / \mu [" \text{yr}^{-1}]$. In order to focus on the directions close to the plane of the sky and minimize projection effects knots only with $d \geq 35"$ and an estimated error on the age smaller than 8 yr
were used. In this selection, 151 knots where left (Fig. 3). The ages vary from 96 to 170 yr. Mean value, weighted by errors, is $118 \pm 12$ yr. Horizontal line indicates the nova age 102.9 yr (from outburst until our first data) and shows that in general knots have suffered only a modest deceleration since their ejection.

Bode et al. (2004) predicted that the SW part of the remnant should be decelerated due to the interaction with the ancient bipolar nebula. The prediction is supported with the radio and X-ray observations. The SW part is a source of a non-thermal (synchrotron) radio emission (Seaquist et al. 1989) and has an highly asymmetric X-ray nebula (Balman 2005). We can test this prediction when comparing the ages from different quadrants: NE $125 \pm 14$ yr, SE $115 \pm 11$ yr, SW $113 \pm 10$ yr, and NW $121 \pm 11$ yr. The lack of deceleration in SW part is obvious. There is no strong evidence for devia-
5. Kinematical Analysis

In order to estimate the distance an assumptions about the real geometry of the GK Per was made. Firstly, proper motion directions $\alpha$ were compared with position angles (PA) of knots in the plane of the sky (left panel Fig. 4) in order to know if the expansion is ballistic. Velocity vectors are generally aligned along the radial direction, but a pattern of non-radial velocities is also observed. The plot of radial velocities as a function of apparent distance from the central star together with the expected distance-velocity plot for spherical shells of radii of 35" and 55" and expansion velocities of 400 and 1000 km s$^{-1}$ (right panel Fig. 4) shows that most of the knots are confined within these limits, suggesting that the knots of the GK Per form a relatively thick shell expanding with a significant range of velocities. Considering the above mentioned and overall roundish morphology of GK Per we consider the remnant to be a quasi-spherical shell in which knots expand purely radially from the centre. With this in hand we can represent the depth of the nebula along the line of sight (Fig. 5). The observer is on the right side. 99 knots with error on spacial distance $R < 10''$ are presented. The extension of the nebula along $Z$ depends on the adopted distance $D$. We assume that the distance value that better corresponds to an overall spherical shape of the nebula is our expansion-parallax determination of the distance. The adopted value, estimated by visual inspection of the variation of the overall shape of the nebula as a function of $D$, is 400±30 pc.

6. Expansion Velocities

Expansion velocity can be calculated as follows: 

$$v_{\text{exp}} = \sqrt{v_{\text{sky}}^2 + v_{\text{rad}}^2}$$

Most knots have $v_{\text{exp}}$ between 600 and 1000 km s$^{-1}$. Such a range of velocities could be due to the initial range of velocities or, due to the dynamical evolution of the two distinct ejecta components. The latter is also supported by the progressive circularization of the SW nebular edge and a relative brightening of the whole eastern side compared to the western part (see animation in Liimets et al. (2012) Fig. 3).

![Figure 4. Assumptions on quasi-spherical shell of GK Per. See text for more details.](image)
Conclusions

The ejecta of GK Per is a thick shell (nearly half of its outer radius) consisting of knots expanding with a significant range of velocities. Since their ejection one century ago, knots have suffered only moderate deceleration, with no clear signs of dependence of the expansion rate on the position angle. The velocity vectors are generally aligned along the radial direction but a symmetric pattern of non-radial velocities is also observed at specific directions. The total $H\alpha+\text{[NII]}$ flux of the nebula seems to be linearly decreasing with time, but with a significant difference between the various quadrants. An improved kinematic distance determination of $400 \pm 30$ pc was obtained. These results raise some problems to the previous interpretations of the dynamical properties of GK Per. In particular, the idea of a strong interaction of the outflow with the surrounding medium in the SW quadrant is not supported by our data, owing to the lack of significant deceleration of the knots along this direction.

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