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Hubble-type outflows of the high excitation, poly–polar planetary nebula NGC 6302 – from expansion proper motions.

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ABSTRACT

The outflowing proper motions of fifteen knots in the dominant northwestern lobe of the high–excitation poly–polar planetary nebula NGC 6302 have been determined by comparing their positions relative to those of faint stars in an image taken at the San Pedro Martir Observatory in 2007 to those in a South African Astronomical Observatory archival plate obtained by Evans in 1956. The Hubble-type expansion of this lobe is now directly confirmed in a model–independent way from these measurements. Furthermore, an unambigous distance to NGC 6302 of 1.17 ± 0.14 kpc is now determined. Also all the velocity vectors of the fifteen knots (and two others) point back to the central source. An eruptive event from within the central torus $\approx$ 2200 yr previously must have created the high speed lobes of NGC 6302.

Key words: ISM planetary nebula:NGC6302

1 INTRODUCTION

The poly–polar planetary nebula NGC 6302 has always attracted interest (see Meaburn et al 2005 - hereafter Paper 1 - and papers therein) because it has an extremely hot star in its central stellar system and because multiple bipolar lobes which emanate from this source reach outflow velocities of ≥ 600 km s^{-1}(Paper 1). Furthermore, a surprisingly massive central CO emitting torus (≈ 2 M$_\odot$ and expanding at 8 km s^{-1}) viewed nearly edge–on, obscures this central stellar system (Matsuura et al 2005; Peretto et al 2007). These authors estimate that this was ejected between 7500 yr and 2900 yr ago. The surface temperature of the hot central star has been estimated most recently from FIR ISO observations as 220,000 K by Wright et al. (2007). This is the lowest temperature yet estimated for the hydrogen deficient central star.

The high–speed outflow of the principal northwestern lobe is Hubble-type i.e. outflow velocity is proportional to distance from the source. This has been conclusively illustrated by the kinematic–morphological modelling of the spatially resolved optical line profile observations in Paper 1, though it was also revealed in a more limited fashion in Meaburn & Walsh (1980). This behaviour alone favours a ballistic origin for the ejecta i.e. simply the gas more distant from the source has been ejected at the highest speed. This Hubble–type assertion would also predict that the velocity vectors of all of the outflowing material in a lobe point directly back to their source.

Estimations of the crucial distance to NGC 6302 (see Paper 1 for a summary) ranged from 0.15 to 2.4 kpc prior to its expansion proper motion (PM) measurement of 1.04 $\pm$ 0.16 kpc reported in Paper 1. The latter value was based on the kinematic–morphological modelling of the northwestern lobe combined with a measurement of the PM of a single compact knot apparent between the 1956 image of Evans (1959) and a comparable image taken in 2001. The prediction that the dynamical age of the northwestern lobe is 1900 yr is also a natural consequence of this PM measurent. This would suggest that the lobe was ejected after the central torus had formed.

The original 1956 plate taken of NGC 6302 by Evans (1959) has now been obtained from the SAAO archive and scanned to permit comparison with a new image of the northwestern lobe taken in 2007. The northwestern lobe is particularly suited to this analysis of its expansion PMs for its axis is close to the plane of the sky and its outflow velocities become high in its extremities and are now well–known (Paper 1). PMs of fifteen nebular knots distributed along the length of the northwestern lobe have now been measured. The confirmation of the Hubble–type nature of the outflow has now been established along this lobe by an independent method as a consequence, as has the ballistic nature of the ejection process. More refined values for the expansion–PM distance to NGC 6302 and the dynamical age of the northwestern lobe have also been derived.

2 OBSERVATIONS AND RESULTS

The baseline photographic plate for the present proper motion measurements was taken with with the 74-inch Radcliffe reflector by Evans (1959) on August 1 1956. This was through a Wratten I205 dye filter which when combined with Kodak 103aE photographic emulsion has a bandwidth of a few hundred angstroms centred on the Hα and [N II] nebular emission lines. The exposure time of 45 minutes left the image of the bright nebular core saturated but revealed most of the northwestern lobe of NGC 6302 (Fig. 1).

The second image of the northwestern lobe (Fig 2) was taken on June 18 2007 with the Manchester Echelle spectrometer (Meaburn et al 2003) in its imaging mode when combined with the 2.1–metre San Pedro Martir telescope. A 100Å bandwidth interference filter isolated the Hα and [N II] lines and a SITE CCD was the detector. Two times binning made each of the 512$\times$512 data taking windows 0.6224$''$ across when projected on to the sky. The exposure time was 60 seconds. The time separation between the two images is then 50.88 yr. The coordinates for the images in Fig. 1 & 2 were derived from stellar positions taken from the POSS digital sky survey and, because of their limited accuracy (a few arcsec) are useful only to identify nebular features.

The 1956 plate was scanned by a transmission, slide scanner to convert the photographic density distribution into a digital array. The digital values in the subsequent array have a complex relationship to the relative surface brightnesses of nebular features; whereas the values within the 2007 CCD image are nearly linearly related. However, the positions of the brighteness maxima of compact nebular knots, a few arcsec across, are closely comparable in both arrays. Fifteen such knots (1–15 in Table 1) in unsaturated areas of the 1956 image of the northwestern lobe of NGC 6302 were identified. Two (16 & 17) are outside this lobe.

A subset of the 1956 data array (Fig. 1), matching the coverage of the northwesterm lobe by the 2007 imagery (Fig. 2), was obtained using the ISUBSET FIGARO software routine and scaled to the same pixel size as the 2007 array using the SQORST KAPPA routine. The separations of stellar images in both arrays were used to derive the scaling factor. Sections of both arrays were then contoured where each section contains some of the knots as well as sufficient images of the faint stars. Examples of the resultant contour maps from this process are shown in Figs. 3a– b for the area marked by a rectangle in Fig. 1.

The shifts of the nebular knots 1–7 listed in Table 1 and identified in Fig. 4 over the 50.88 yr base line are immediately apparent when the positions of their brightness maxima are compared to those of the stellar images in Figs. 3a & b. The faint stars with PMs $\leq 0.3''$ over the same baseline are easily identified by measuring their image positions relative to the other faint star positions in the same array. For example, of the five faint stellar images common to both contour maps in Fig. 3a–b (marked S1,S3-6) only that marked S4, to the bottom left of both arrays, shifted by this amount over the 50.88 yr baseline (the bright star also marked S2 to the top of the array was considered unreliable for this purpose). The differences in the positions of the knots 1–7 were then measured by comparing their shifted positions to the unshifted mean positions of the four remaining faint stars in this example i.e. S1, S3, S5 & S6. Three further contour maps covering knots 8–17 were used in an identical manner. The results of this process are listed in Table 1 and illustrated graphically in Fig. 5. Repeated measurements of the contour maps illustrated that the shift in the position of each knot had been derived to $\pm$ 0.3$''$ accuracy which gives rise to the error bar for all the PM measurements of 6 mas yr^{-1} in Fig. 5 where these PMs are plotted versus separation from the central thermal radio source (Terzian, Balick & Bignell 1974) and infrared point source (Danziger et al 1973). This position (see Table 1) is also the centroid of the CO map of the core of NGC 6302 (Peretto et al 2007). The measurements of the directions of the motions of most of the knots by the same process are accurate to $\pm$ 2° except for the two elongated knots (10 and 17 in Fig.4) where the uncertainty is a few times this amount.

3 DISCUSSION

3.1 Hubble–type expansion

In Paper 1 a Hubble–type expansion of the northwestern lobe of NGC 6302 was indicated after the observed radial velocities were compared with the predictions of a morphological-kinematical model. The starting point for this modelling came simply from the pv array (fig. 4 of Meaburn & Walsh 1980) across the lobe at 1.71$'$ from the central source. This revealed that the axis of the lobe is inclined at only ϕ = 12.8° $\pm$ 2° to the plane of the sky with its nearside edge flowing away from the source nearly in the plane the sky (see fig 13 Paper 1). An outflow velocity of 263 $\pm$ 20 km s^{-1} was then derived at this position. From this starting point the more extensive motions over the northwestern lobe in Paper 1 matched closely the model predictions where a Hubble–type expansion, with the motions of all parts of the lobe directed away from the central source, are both assumed.

The measurements of the PMs and their flow directions of 15 nebular knots in the northwestern lobe therefore permit the validity of both of these predictions to be examined directly: the fortuitous small value of ϕ and the high elongation of the lobe mean that no modelling is necessary in the interpretation of the results. The linear increase in PM with distance along the northwestern lobe, as expected for Hubble–type motions, is clearly shown in Fig. 5. Moreover the velocity vectors in Fig. 4 are all directed away from the central source at RA(2000) 17:13:44.48, DEC(2000) -37:06:14.7 (Table 1) within the measurement uncertaintities of $\pm$ 2° for each vector.

The conclusions of Paper 1 are therefore directly confirmed: the knots were ejected in the same short–lived eruptive event and have travelled outwards ballistically for around 2200 $\pm$ 100 yr (the weighted mean of the very similar PM dynamic ages given in Table 1); with the fastest travelling proportionally furthest. The larger mean dynamical age of the knots 16 and 17 (see Table 1 and Fig. 4) could marginally indicate that these were emitted at a somewhat earlier time than the dominant northwestern lobe.

3.2 Distance

The most accurate distance D (kpc) to NGC 6302 up to that date is derived in Paper 1 as 1.04 ± 0.16 kpc using the PM of Knot 2 (Fig. 4) whose 1956 position was measured with a ruler off an enlargement of the published figure in Evans (1959). The present work has improved the measurement of the PM of Knot 2 and now determined those of 14 other knots in the northwestern lobe (Table 1).There was always the possibility that deriving D from one knot alone as in Paper 1 would give an anomolous answer.

The relationship of D, PM and outflow velocity V along a line at an angle ϕ to the plane of the sky is:

$$\mathrm{D(kpc)} \times \mathrm{PM(mas\ y^{-1})} = 0.2168 \times \mathrm{V\ (\ km\ s^{-1})} \times \cos(\phi) \qquad (1)$$

and for V = 263 km $\mathrm{s^{-1}}$, at $1.71'$ from the central source and for $\phi = 12.8^\circ$ (for the axis of the northwestern lobe). Assuming a Hubble–type outflow then for a knot at *x*(arcmin) from the central source (column 5 in Table 1),

$$\mathrm{D(kpc)} = 32.51 \times x\mathrm{(arcmin)} \times (\mathrm{PM(mas\ y^{-1})})^{-1}. \qquad (2)$$

The values derived for D of each knot (column 7 in Table 1) are for the angular separations given in column 5 combined with the PMs in column 3 derived with equ. 2. The random errors in column 7 are a consequence only of the ± 6 mas $\mathrm{y^{-1}}$ uncertainty on each PM value in column 3. The weighted mean of D from the values in column 7 is therefore 1.17 kpc. The uncertainty in this weighted mean is ± 0.03 kpc if only the standard deviation of the error values in column 7 of Table 1 are taken into account. The actual weighted mean standard deviation of the values for D in column 7 of Table 1 is ± 0.09 kpc. This discrepency indicates that either the knots themselves have a significant dispersion of outflowing velocities around the Hubble–type prediction or that a further source of random uncertainty is present. The most likely origin for the latter is that ϕ for an individual knot can range from $\pm\ 12.8^\circ$ around the lobe axis at $\phi = 12.8^\circ$ (see Paper 1) then $\cos(\phi)$ in equ. 1 can have values from 1 to 0.9 depending whether or not a knot is towards the nearside or farside of the northwestern lobe, which cannot be determined in the present observations. The actual standard deviation around the weighted mean value of $\approx \pm\ 0.1$ kpc of the D values in Table

1 which were derived assuming all the knots had the same ϕ then most likely reflects this angular spread of the outflow. In addition, a systematic uncertainty is present in the mean value of D due to the use of V = 263 ± 20 km s^{-1} at $x = 1.71'$ from Paper 1 in equ. 2 therefore D = 1.17 ± 0.14 kpc is a realistic best value, with a conservative estimation of the uncertainty, for the distance to NGC 6302.

Since there is excellent evidence of both velocity increasing linearly with distance (Hubble law expansion) and PM vectors pointing back to the central source, and therefore an eruptive event as origin of lobes, then fragmentation of the eruption that is channeled perpendicular to the thick torus explains all of above plus the formation of the poly-polar or multi- polar structures in a natural way, i.e. all ‘lobes’ are formed at the same time through the splitting or fragmentation of the mass participating in the eruptive event. Evidence of this fragmented mass is clearly appreciated in the HST images of the core of NGC 6302 presented by Matsuura et al (2005). Furthermore, the outflowing velocities of ≥ 600 km s^{-1} (Paper 1) for the knotty extremities of the northwestern lobe of NGC 6302 are similar to those of the knots in the Hubble-type outflow of the Hourglass Nebula MyCn 18 (Bryce et al 1997; O’Connor et al, 2000). Similar eruptive processes must have been in play. Steffen & López (2004) demonstrated theoretically that some of these properties could be generated by a fast wind blowing through a clumpy medium. This however, is an unlikely mechanism for the creation of the NGC 6302 lobes for there is no direct evidence of a fast wind (Paper 1), the fastest knots are the densest (1000 cm^{-3} - Meaburn & Walsh, 1980) contrary to their predictions and the ≥ 600 km s^{-1} outflow speeds are too high. More probably the present outflow is the consequence of a nova–type explosion or an eruptive event channeled down the rotation axis of a close binary system.

4 CONCLUSIONS

A Hubble–type outflow has been shown to be occurring directly from PM measurements of 15 knots in the northwestern lobe of NGC 6302. This confirms the model–dependent prediction of the same behaviour from radial velocity measurements in Paper 1 (and see Corradi 2004 for similar behaviour in other PNe).

The velocity vectors of these 15 knots in NGC 6302 point back to the central source.

The outflowing velocities of ≥ 600 km s^{-1} at the furthest extremities of the northwestern lobe are confirmed.

The northwestern lobe of NGC 6302 must then have been created in an eruptive event ≈ 2200

Table 1. Column 1 gives knot identication from Fig.4. Knots 1–15 are in the northwestern lobe. Column 2 gives the RA and DEC (2000 coords) from the 2007 image. These are for identification purposes only and are not accurate enough (± 1″) for future proper motion measurements.Column 3 gives the PM of each knot derived from the displacement between its 1956 and 2007 positions. All values are derived conservatively to ± 6 mas yr^{-1} accuracy.Column 4 contains the position angles of the direction of motion between these dates to ± 2° accuracy for all but 10 and 17 (see text). Column 5 gives the separation of each knot from the central compact radio source (RA(2000) 17:13:44.48, DEC(2000) -37:06:14.7 from Terzian, Balick & Bignell 1974). Column 6 gives the proper–motion dynamical age of each knot. Column 7 gives the distance to NGC 6302 derived from the values in columns 3 & 5 with the uncertainties derived from the ± 6 mas yr^{-1} in the PM values in column 3.

1. **Knot**	2. **Position** **RA,DEC(2000)**	3. **PM** **mas yr^{-1}**	4. **PA** **deg**	5. **Angular separation** **arcmin**	6. **Dynamic age** **yr**	7. **Distance** kpc
1)	17:13:30.66, -37:05:22.2	78.6	287	2.95	2250	1.22 ± 0.09
2)	17:13:34.15, -37:05:15.2	68.7	304	2.28	1990	1.08 ± 0.09
3)	17:13:31.29, -37:05:17.9	64.9	289	2.06	1910	1.03 ± 0.10
4)	17:13:31.07, -37:05:30.3	74.7	283	2.84	2280	1.24 ± 0.10
5)	17:13:32.38, -37:05:18.7	70.8	295	2.58	2190	1.23 ± 0.10
6)	17:13:32.84, -37:05:25.0	64.9	289	2.46	2280	1.23 ± 0.11
7)	17:13:32.89, -37:05:38.7	66.8	289	2.39	2150	1.16 ± 0.11
8)	17:13:33.72, -37:05:44.4	55.0	289	2.21	2410	1.31 ± 0.14
9)	17:13:34.71, -37:05:38.9	59.0	303	2.04	2080	1.12 ± 0.11
10)	17:13:35.38, -37:05:47.1	55.0	280	1.94	2110	1.15 ± 0.13
11)	17:13:35.53, -37:05:57.0	49.1	283	1.81	2210	1.20 ± 0.15
12)	17:13:36.41, -37:06:00.9	39.3	264	1.63	2480	1.35 ± 0.21
13)	17:13:38.91, -37:06:03.7	25.6	273	1.12	2630	1.42 ± 0.33
14)	17:13:40.01, -37:05:47.6	29.5	292	1.06	2160	1.26 ± 0.26
15)	17:13:39.86, -37:05:35.8	35.4	306	1.07	1820	0.98 ± 0.17
16)	17:13:33.23, -37:06:28.5	39.3	271	2.26	3450	
17)	17:13:33.49, -37:06:24.8	55.0	256	2.20	2400	

yr ago but probably after the creation of the central torus 2900 - 7500 yr ago as estimated by Matsuura et al (2005) & Peretto et al (2007).

The distance to NGC 6302 is now determined unambiguously as D = 1.17 ± 0.14 kpc.

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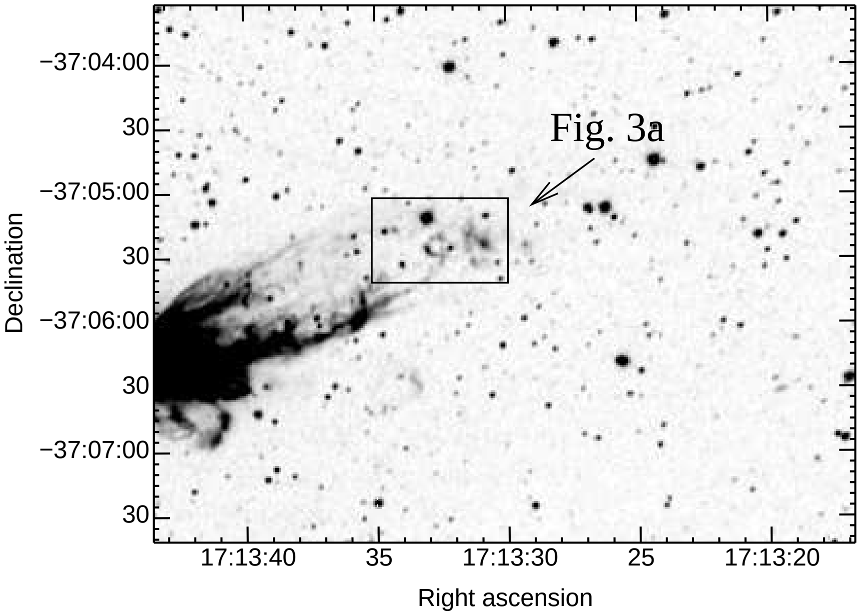

Figure 1. A section from the red 1956 photographic plate taken by Evans (1959). This is a subset covering only the northwestern lobe of NGC 6302. The nebular lines Hα and [N II] were isolated by the bandwidth. The rectangle identifies the area contained within the contour map in Fig. 3a

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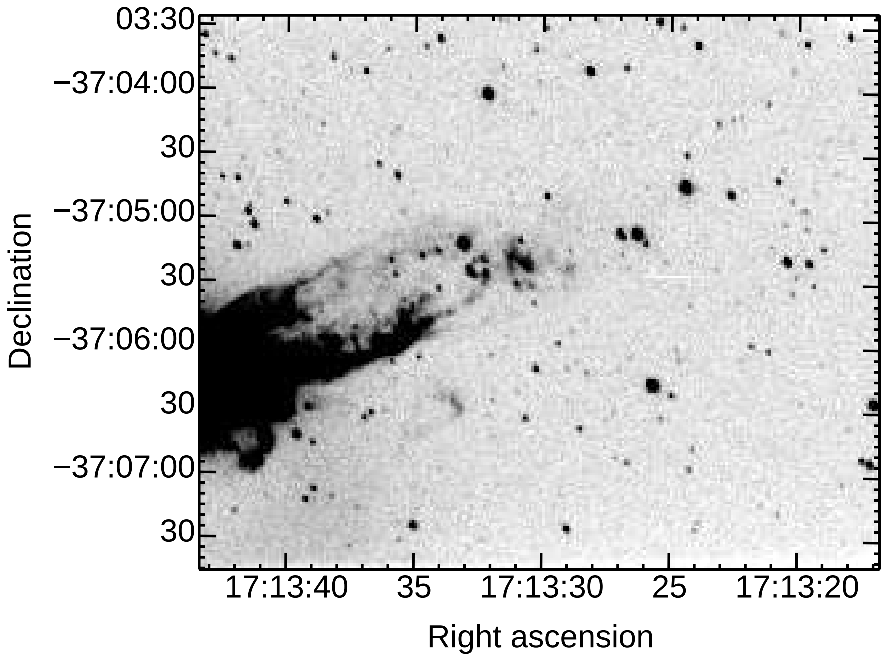

Figure 2. The same area of NGC 6302 as shown in Fig. 1 but obtained in 2007. The same nebular lines were transmitted.

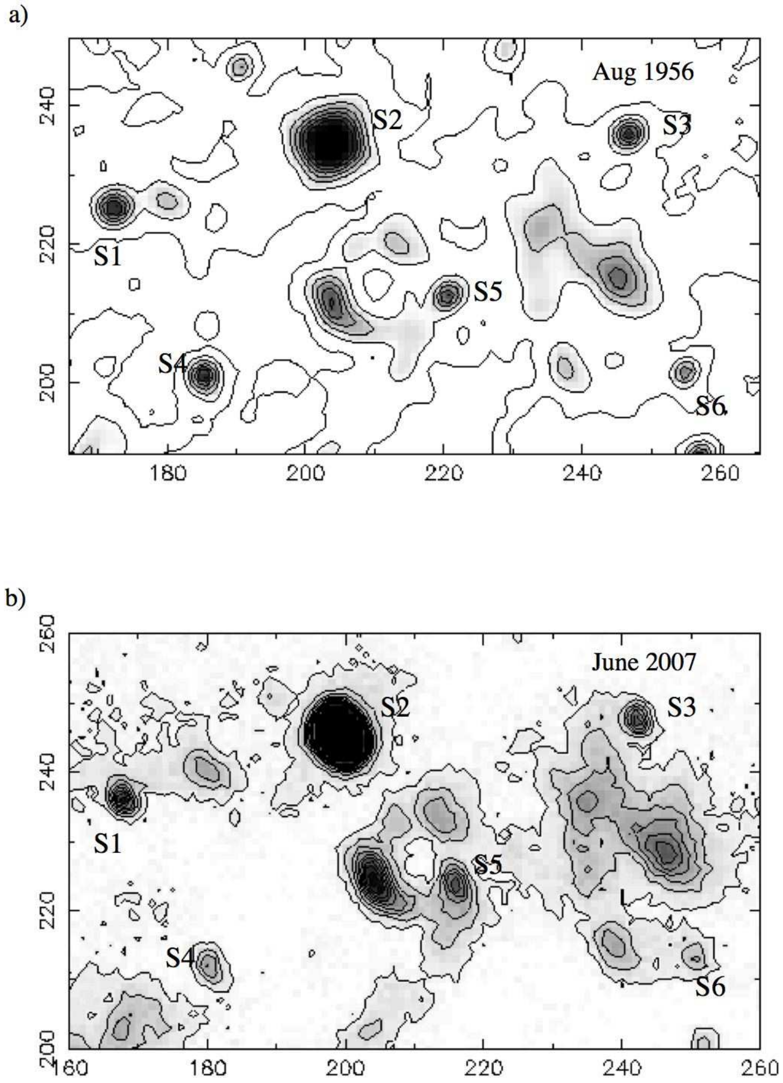

Figure 3. a) A contour map and negative greyscale presentation of the subset of the 1956 plate whose area is identified in Fig. 1. Star images are identified by 'S1–6' and the contours of knots 1–6 can be seen and identified from Fig. 4. b) As for Fig. 3a but for the CCD image taken in 2007.

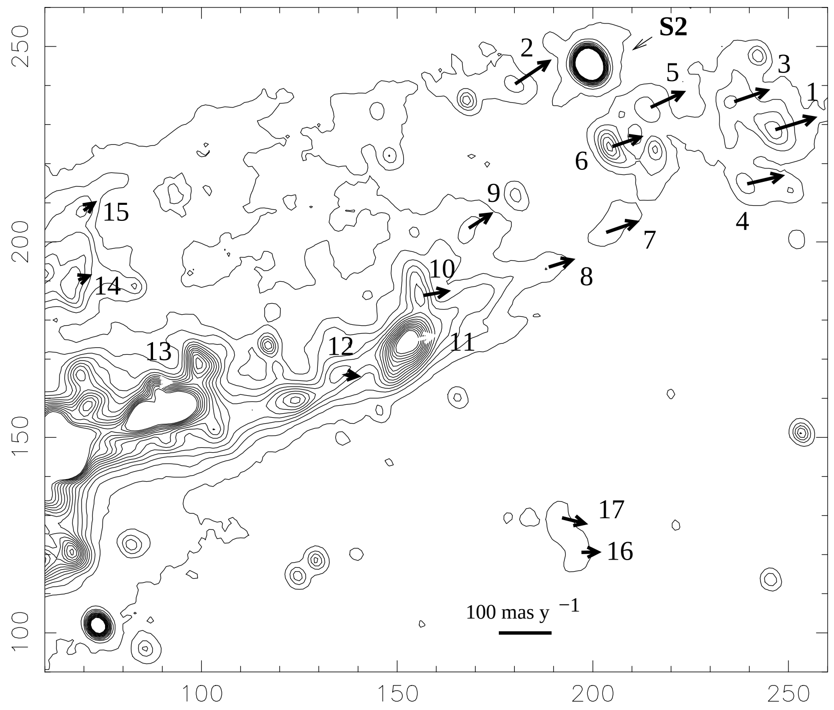

Figure 4. A contour map is presented of that part of the northwestern lobe in the 2007 CCD array that contains the knots 1–15 and the southern feature knots 16–17. The expansion PM vectors are taken from their values in Table 1. The extent of the displacement is from the tip of each arrow to the end of its tail. Note that the arrows for knots 11 and 13 are white to show against packed contour lines. The star S2 from Figs. 3a & b is identified to aid the comparisons between these contour maps.

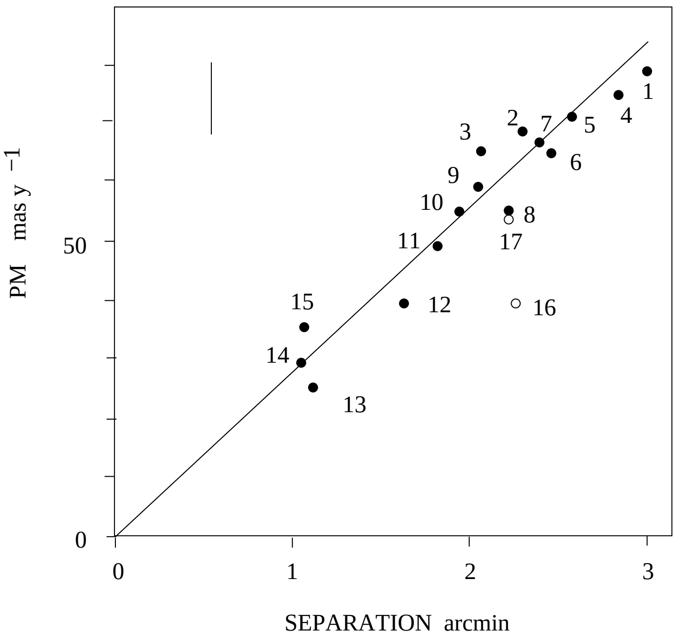

Figure 5. The PMs of knots 1–17 are shown against their separation from the obscured, central, source. The errors in each displacement ± 0.3″ for each knot over the 50.88 yr baseline is nearly the same and, because of the Hubble-type expansion translates to an error of ± 6 mas yr^{-1} for all of the proper motions. Knots 16 and 17 are shown as white circles for the do not belong to the northwestern lobe. A weighted mean, least squares best fit straight line is shown for the northwestern lobe knots only.