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THE DISCOVERY OF A BIPOLAR, ROTATING, EPISODIC JET (BRET) IN THE PLANETARY NEBULA KjPn 8

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ABSTRACT

A spectacular (≃14′ × 4′) bipolar nebula, with a symmetric and rotating, high-velocity collimated outflow, with episodic outburst properties, has been discovered in the Cassiopeia-Cepheus region. A compact object classified as the planetary nebula KjPn 8 is located at the center of symmetry of this extraordinary nebula. The angular extent of this bipolar structure is now the largest one known associated with a planetary nebula (PN). A mosaic of Hα images covering the full extent of the nebula is presented, as well as [N II] λ6584, [S II] λ6724, [O II] λ3729, and [O III] λ5007 images of the central (≃5′ × 5′) region. These images reveal symmetric pairs of bow shocks which are located at different position angles, in a way expected from a rotating, episodic jet. Low-dispersion spectroscopy of regions of the bipolar lobes confirms their shock-excited nature. The core is of low excitation class and seems nitrogen enriched. Our 3.5 cm VLA observations yield a first radio detection of the core of KjPn 8.

Subject headings: ISM: jets and outflows — planetary nebulae: individual (KjPn 8)

1. INTRODUCTION

Bipolar, rotating, episodic jets (BRETs) in planetary nebulae (PNs) are characterized by the presence of symmetric collimated flows producing shock-excited regions from episodic outbursts. The spatial distribution of the shocked regions indicates rotation, or precession, of the main symmetry axis of the episodic jet. These shock-excited regions, which are interpreted as the leading fronts of intermittent jets, may be several times larger than the planetary nebula itself. Collimated bipolar outflows have been known to exist in other astronomical objects, such as quasars and active galactic nuclei, high-energy binary systems, and young stars. In all these objects, an accretion disk is believed to play a key role in the acceleration and collimation of the bipolar flows, although a detailed model has yet to be produced. In the case of PNs, the existence of bipolar jets is even more of a puzzle, since accretion disks are not an established component in this type of source (see, however, Soker & Livio 1994). The BRET prototype in PNs is Fleming 1 (López, Roth, & Tapia 1993; López, Meaburn, & Palmer 1994; Palmer et al. 1995). Another likely member of this class is NGC 6543; Harrington & Borkowski (1994) have obtained *Hubble Space Telescope* images that reveal the presence of symmetric, precessing jets in this object. Furthermore, Bobrowsky et al. (1995) have recently found three pairs of shock-excited knots, symmetrically opposed on either side of He 3–1475, and inmersed within a double, high-velocity jet system. The pairs of knots are located at different position angles, thus also yielding all the characteristics of a BRET. In addition, some of the objects described by Schwarz, Corradi, & Melnick (1992) as exhibiting point symmetry and recently modeled by Cliffe et al. (1995), assuming the presence of an episodic precessing jet in these nebulae, seem also to be related to the BRET phenomenon.

In the present work, we report the discovery of a yet more spectacular candidate for this BRET classification, associated with the PN KjPn 8, where a giant, but faint, bipolar halo, with diametrically opposite pairs of collisionaly ionized knots, has been found. The core of KjPn 8 (PK 112−00 1; PN G112.5−00.1) was first identified as a PN by Kazarian & Parsamian (1971) and listed as object 8 in their original paper. It was later found independently by Kohoutek (1972, 1977), who assigned it the number K3-89. The object has been listed as a true PN by Sabbadin (1986) from R/IR plates and spectroscopic arguments. Zijlstra, Pottasch, & Bignell (1989) included KjPn 8 in their 5 GHz survey of PNs, but they were only able to set an upper limit of ∼1 mJy for this source.

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2. OBSERVATIONS AND RESULTS

The faint bipolar nebula surrounding KjPn 8 was discovered on the night of 1994 September 14 with the 2.1 m f/7.9 telescope at San Pedro Mártir, in combination with a Tektronix 1024^2 CCD (López, Gutiérrez, & Valdez 1995a) and the MEXMAN filter wheel (López et al. 1995b). The nominal field of the CCD is $5'.12 \times 5'.12$, with 24 μm size pixels each $\equiv 0''.3 \times 0''.3$. A mosaic of nine overlapping images, covering the full extent of the nebula, was obtained through a filter centered on Hα and of 11 Å half-power beamwidth (HPBW). This mosaic is presented in Figure 1 (Plate L11). Images of the central region, obtained in the light of [N II] λ6584, [S II] λ6716 + 6731, [O II] λ3727 + 3729, and [O III] λ5007, taken through 10, 54, 46, and 52 Å HPBW filters, respectively, are presented in Figure 2 (Plate L12). All images are 1800 s integration each. Seeing conditions varied from $1''.2$ to $2''.0$ during the observations. Figure 3 is a sketch of KjPn 8 in which its main morphological features are indicated.

The low-dispersion spectroscopy was obtained also with the 2.1 m SPM telescope, using a B&Ch spectrometer and the same Tektronix CCD on the nights of 1994 November 30 and December 2. A 300 lines mm^{-1} grating and 220 μm slit width ($\equiv 2''.9$) yielded a wavelength coverage from 3400 to 7500 Å at a resolution of 9 Å. Integration times ranging from 300 to 1800 s for five slit positions were obtained. In Figure 4 the log Hα/[N II]$_{6548+6583}$ versus log Hα/[S II]$_{6716+6731}$ line ratios from the core and regions A1, A3, B1, and C1 are compared with those for various types of nebulae. Slit positions are indicated in Figure 3. Reduction of the images and spectra was performed in the usual way with the IRAF package.

The 3.5 cm continuum observations of the KjPn 8 field were made during 1994 October 21 using the Very Large Array

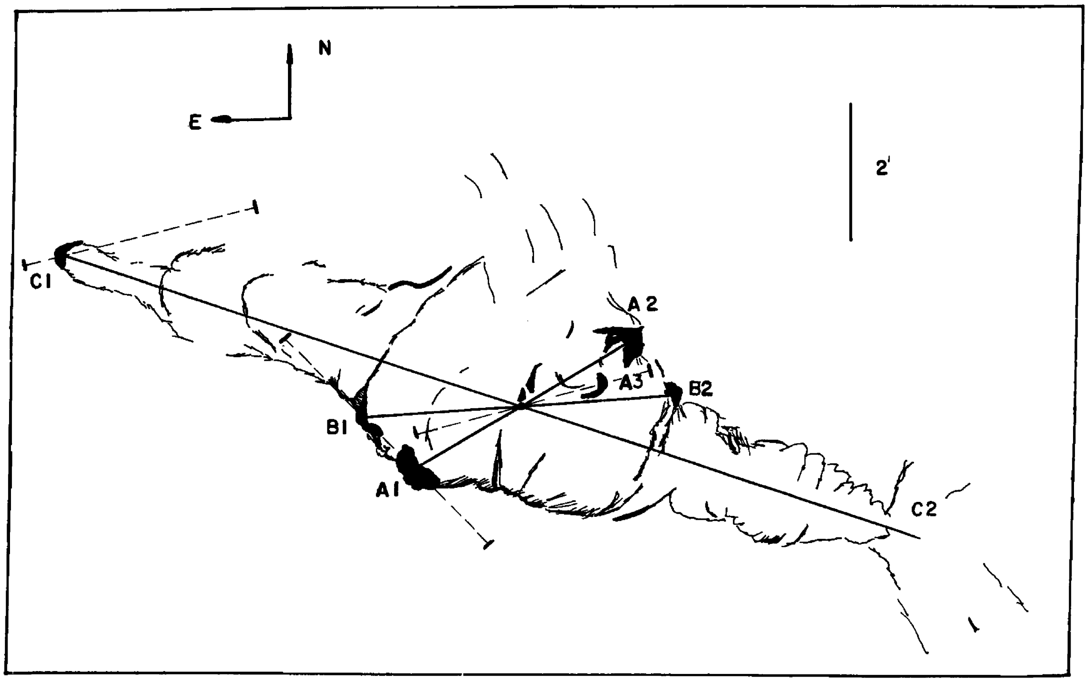

FIG. 3.—A sketch of KjPn 8 in which diametrically opposite shock-excited regions (labeled A–C) have been indicated; lines joining these symmetric regions, and crossing the core, have been drawn. These lines define three aparent axes of symmetry. Slit positions are indicated by dashed lines.

(VLA) of the NRAO[3] in the C configuration. The absolute amplitude calibrator was 0134 + 329, with adopted flux density of 3.30 Jy at 3.5 cm. The phase calibrator was 2229 + 695, for which a bootstrapped flux density of 0.369 ± 0.001 Jy was obtained. The observations were made in both circular polarizations with an effective bandwidth of 100 MHz. The data were edited and calibrated following the standard VLA procedures and using the software package AIPS.

[3] The National Radio Astronomy Observatory is operated by Associated Universities Inc., under cooperative agreement with the National Science Foundation.

We detected a source at the position of KjPn 8. The position of the source is $\alpha(1950) = 23^h21^m55\overset{s}{.}87 \pm 0\overset{s}{.}03$ and $\delta(1950) = 60°41'02\overset{''}{.}0 \pm 0\overset{''}{.}2$. The total flux density of the source is 0.77 ± 0.04 mJy. A least-squares Gaussian ellipsoid fit to the source using the AIPS task IMFIT gives a deconvolved angular size at half-maximum of $2\overset{''}{.}8 \times 1\overset{''}{.}6$, with the major axis aligned at a position angle of 45°. These deconvolved dimensions should, however, be determined more confidently with a higher angular resolution measurement since they are comparable with those of the synthesized beam of $3\overset{''}{.}5 \times 2\overset{''}{.}7$, with position angle of 58°.

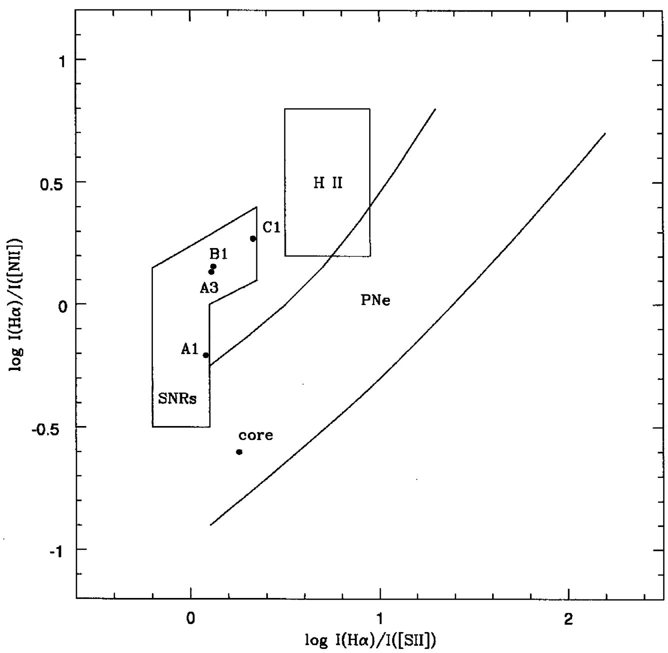

FIG. 4.—The log Hα/[N II]$_{6548+6583}$ vs. log Hα/[S II]$_{6716+6731}$ line ratios from the core and regions A1, A3, B1, and C1 are compared with those for various types of nebulae from Sabbadin et al. (1977).

3. DISCUSSION

3.1. *Morphology*

The typical morphology of a bipolar, rotating, episodic jet in planetary nebulae is found in the prototype Fleming 1 (López et al. 1993). The interpretation of Fleming 1 as a BRET has been kinematically substantiated by López et al. (1994) and Palmer et al. (1995). KjPn 8 has now been discovered as the newest, and so far most spectacular, addition to this familiy. Its angular size (≃14′ × 4′) ranks it as the largest bipolar structure associated with a PN known to date, even larger than He 2-111 (Webster 1978).

The morphological elements of KjPn 8 deserve a thorough investigation and description. Here we point out its main features. On the large scale, the nebular envelope of KjPn 8 resembles a symmetric double nozzle with additional inner bipolar regions rotated with respect to the large structure. The sketch of KjPn 8 indicates diametrically opposite shock-excited regions, labeled A–C (see Figs. 1–3); lines joining these symmetric regions have been drawn, all of which cross the

TABLE 1A

OBSERVED LINE INTENSITIES RELATIVE TO Hβ

λ_0 (Å)	Ion	Core	Core (extinction corrected)	A1	A3	B1	C1
3726 + 29	[O II]	217	338	337	309	528	...
3868	[Ne III]	20	30	23	...	...	...
3967 + 70	[Ne III] + H 8	13	19	...	...	...	...
4101	Hδ	17	23	...	...	...	...
4340	Hγ	37	46	27	34	25	...
4471	He I	7	8	...	...	...	...
4861	Hβ	100	100	100	100	100	100
4925	He I	2	2	...	...	...	...
4959	[O III]	98	94	50	...	...	...
5007	[O III]	298	280	122	43	41	85
5198	[N I]	16	14	62	62	69	...
5755	[N II]	9	6	...	...	...	...
5876	He I	47	34	31	27	60	...
6300[a]	[O I]	89	55	761	689	1648	791
6364[a]	[O I]	28	17	215	220	448	249
6548	[N II]	455	263	282	114	153	137
6563	Hα	495	285	676	534	737	1111[a]
6583	[N II]	1433	820	807	279	361	404
6678	He I	17	10	22	14	24	...
6716	[S II]	131	73	339	240	365	338
6731	[S II]	125	69	222	174	193	199

B. OTHER PARAMETERS

Parameter	Core	Core (extinction corrected)	A1	A3	B1	C1
Slit	2″9 × 4″7	2″9 × 4″7	2″9 × 14″1	2″9 × 2″8	2″9 × 16″3	2″9 × 2″8
log [F(Hβ)]	−13.468	...	−13.684	−14.541	−14.001	−15.125
log [I(Hβ)]	...	−12.72	...	...	...	...
C (Hβ)	...	0.75	...	...	...	...
N_e ([S II])	...	300 cm^{-3}	...	...	...	...
T_e ([N II])	...	7500 K	...	...	...	...

[a] Poor sky subtraction.

core. These lines define three apparent axes of symmetry. The major axis, defined by C1–C2, is aligned at a position angle of ~71°. Axes A1–A2 and B1–B2 are tilted by ~50° and 20° with respect to axis C1–C2, respectively, suggesting the presence of a bipolar, rotating, episodic jet.

The southwestern end, labeled C2, seems to be impacting and dispersing into a nearby interstellar cloud, although this apparent interaction may simply be attributable to a projection effect. Most notable also, on this side, are the multiple-barrel structures leading to the end of the flow. On the opposite, northeastern side, the leading front is shaped into a "pointing finger" structure, labeled C1. Its morphology suggests a velocity enhancement in the region via nozzle channeling of the flow, or interaction of the precessing jet with the ambient medium (see Cliffe et al. 1995). The northern part of the central region (cylinder) seems to have burst and an outflow set probably owing to pressure differences.

The other two bipolar structures, defined by axes A1–A2 and B1–B2, are located nearer to the core and show highly filamentary and knotty structures. These structures presumably represent late manifestations of the BRET activity. The central 5′12 × 5′12 region of KjPn 8 has been imaged in low- and high-excitation species. This region contains the shock-excited regions A1, A2, B2, and A3 labeled in Figure 3. The corresponding images are presented in Figure 2. These filamentary lobes show conspicuous emission in the forbiden lines of [N II], [S II], [O II], and, to a lesser extent, [O III]. All these images show indications of bow shock structures. The emission from the higher excitation [O III] line usually appears when the shock velocity $V_s > 100$ km s^{-1} (see, e.g., Hartigan, Raymond, & Hartmann 1987). From the corresponding image in Figure 2, one can see that the [O III] emission is mainly concentrated on the brightest bow shock structures (A1–A2), near their apex, where one expects that the perpendicular component, $V_\perp$, of the incident shock velocity V_s is large. The presence of large shock velocities associated with these symmetric, collimated outflows is confirmed by the line ratios presented in the next section.

3.2. *Spectroscopic Line Ratios*

Spectra were obtained from the core and regions A1, A3, B1, and C1, indicated in Figure 3. In Table 1A are listed the observed fluxes for the main nebular lines detected in our spectra for the different positions observed. The uncertainties in the line fluxes are of the order of 20% and 10% for weak and strong lines, respectively; dashes indicate that the line was either absent or too weak to be measured. The core position has been dereddened with its corresponding Hα/Hβ/Hγ decrement. Table 1B lists the areas of the slit over which the fluxes for the corresponding positions were extracted. In the case of the core, its size is nearly comparable to the entrance slit. We measure from the Hα and [O III] images an FWHM size for the core of 3″6 and 2″8, respectively. The former is very similar to the size of 3.″8 quoted in the ESO-Strasbourgh catalog of galactic PNs, whereas the latter fits well the size derived from our radio map. It would seem that the larger size of the core in Hα is real, not attributable to poorer seeing conditions, for instance, suggesting the presence of a scattering component at this wavelength. Our derived Hβ intensity for the core coincides well with the value derived by Acker et al. (1991) of log Hβ = -12.8 ± 0.2; however, they quote an angular size for the core of 13″ and correct their measured value for this nebular extension, which is larger than the entrance size of their slit. For the reasons given above, we believe that 13″ diameter may be a misprint because such a large size is inconsistent with our observations.

It is of interest to compare the expected Hβ value from our VLA observations with the measured one. Assuming that the nebula is optically thin in both Hβ and radio continuum, an average electron temperature of $T_e = 10^4$ K, and that there is no extinction, the flux densities of these two processes should be related by

$$S_{(3.5\,\mathrm{cm})} = 2.7 \times 10^{12} S_{(\mathrm{H}\beta)},$$

with $S_{(3.5\,\mathrm{cm})}$ in mJy and $S_{(\mathrm{H}\beta)}$ in ergs cm^{-2} s^{-1}. Since we measure $S_{(3.5\,\mathrm{cm})} = 0.77$ mJy, we expect that $S_{(\mathrm{H}\beta)} = 2.9 \times 10^{-13}$ ergs cm^{-2} s^{-1}, in reasonable agreement with our dereddened Hβ flux from the core that yields 1.9×10^{-13} ergs cm^{-2} s^{-1}. On the other hand, from the value obtained for C(Hβ), we find a value for $E_{B-V} = 0.51$. These numbers indicate that only modest extinction is present along the line sight.

We have plotted in Figure 4 the log Hα/[N II]$_{6548+6583}$ versus log Hα/[S II]$_{6716+7631}$ line ratios on a diagnostic diagram (Sabbadin, Minello, & Bianchini 1977) for radiatively ionized galactic H II regions, planetary nebulae, and collisionally ionized supernova remnants. This diagram allows a straightforward appreciation of the dominant excitation mechanisms prevalent in these regions. Our spectra confirm that shock conditions are present in all the filamentary regions observed, including the extreme position C1, and they lead to the interpretation of these being the working surfaces of high-velocity collimated flows. The position for the core in this diagram lies in the region corresponding to PNs, with low Hα/[N II] ratios; this suggests that the spectrum from the core of KjPn 8 is predominantly radiatively ionized and very likely nitrogen enriched, although contribution of shocked outflowing material should also be present, since the Hα/[S II] ratio is also low. The outer, filamentary lobes are collisionally ionized by shocks; a very similar situation is found in He 2–111 (Meaburn & Walsh 1989). The excitation is low in the core; this may indicate that KjPn 8 is a relatively young PN, though further spectroscopic analysis of the core properties at higher resolution are desirable to establish firmly its characteristics. By comparing the line intensities in Table 1 with models of radiative bow shocks (e.g., Hartigan et al. 1987), we find the best agreement for models with shock velocities of 200–300 km s^{-1}.

3.3. *Distance and Size*

KjPn 8 is located in the Galactic plane very near the H II complex S162, whose southernmost filaments are visible at the northwest corner of Figure 1. S162 is located at a distance of 3.5 kpc (see Christopolou et al. 1995, and references therein); given the low extinction values to KjPn 8, discussed in the preceeding section, it is most unlikely that any physical connection exists between these two objects. Considering that for KjPn 8 $E_{B-V} = 0.51$ and that the mean selective extinction in the galactic disk scales with distance d as $\langle E_{B-V}\rangle/d = 0.61$ mag kpc^{-1} (Spitzer 1978), we prefer to tentatively adopt a distance to KjPn 8 of 1 kpc. With this distance, the angular dimensions transform into 4.1×1.2 pc.

4. CONCLUSIONS

The discovery of the largest bipolar structure associated with a PN and showing the characteristics of a bipolar, rotating, episodic jet (BRET) is reported. Shock conditions are shown to be present in this filamentary object. The core of KjPn 8 has been detected for the first time at 3.5 cm with the VLA. Modest extinction is derived along the line of sight, suggesting a distance to the object of ≃1 kpc. Higher spatial resolution is now required to explore the core structure, both in the radio and optical domains. Also, high spectral resolution, long-slit spectroscopy is now needed to kinematically probe the BRET nature of KjPn 8 and to evaluate the parameters powering this extraordinary object.

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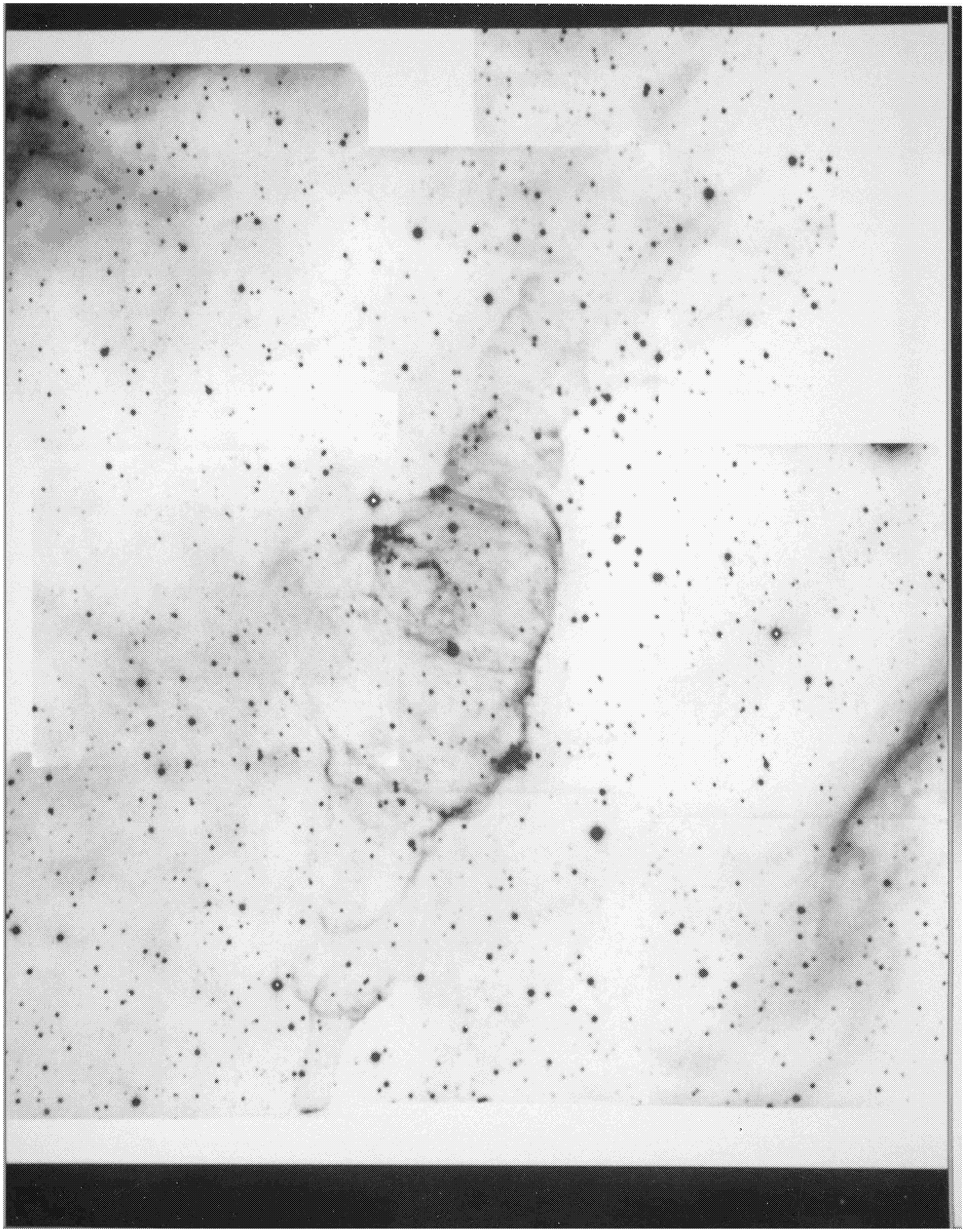

FIG. 1.—Hα mosaic of KjPn 8 composed of nine 1024^2 frames and covering the full extent of the bipolar envelope. North is up, and east is to the left. Each CCD frame is 5'.12 on its side.

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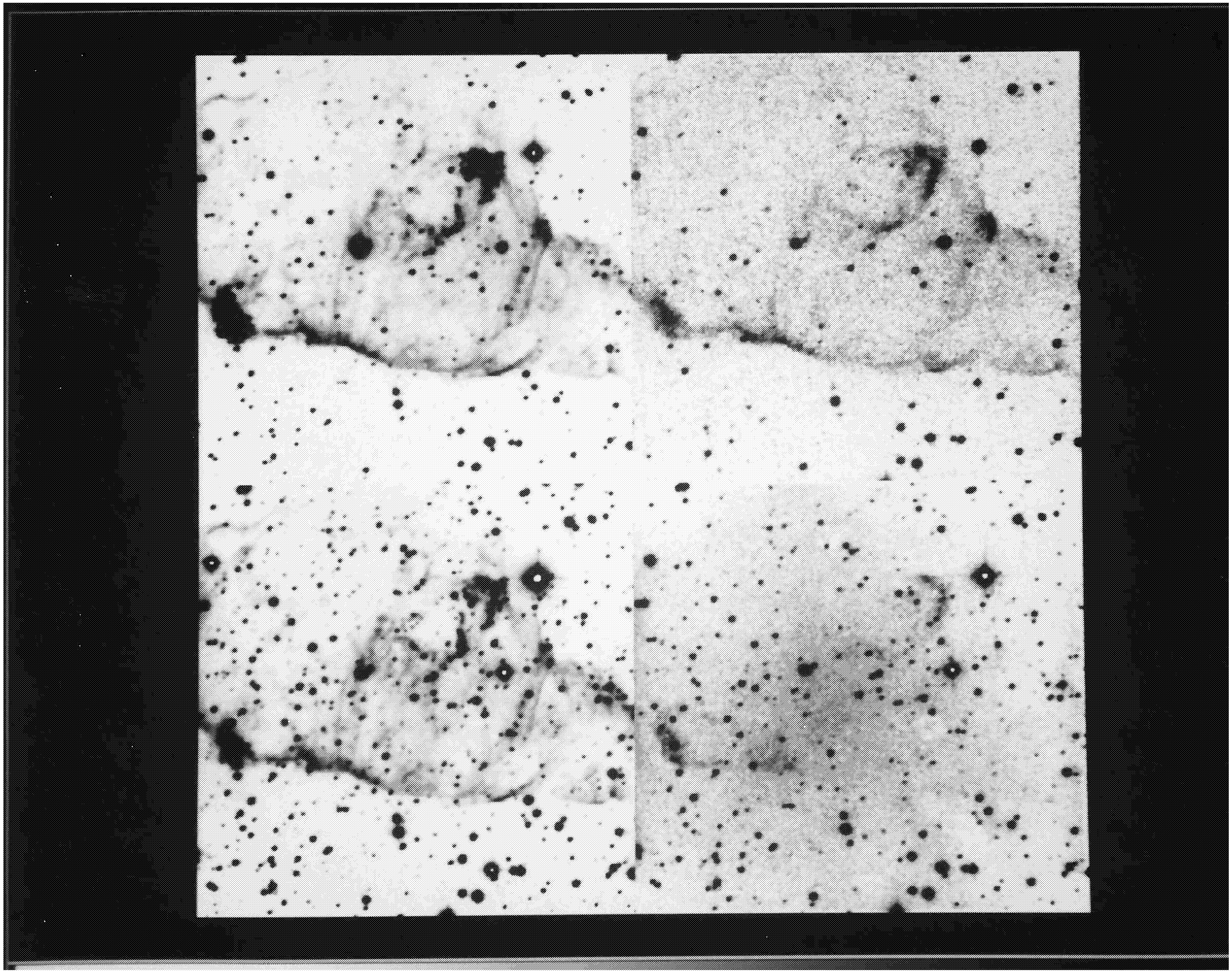

FIG. 2.—Images covering the central 5′.12 × 5′.12 of KjPn 8 taken through [N II] λ6584 (*top left*), [O II] λ3729 (*top right*), [S II] λ6724 (*bottom left*), and [O III] λ5007 (*bottom right*). North is up, and east is left.

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