Astron. Astrophys. 156, 301–309 (1986)

ASTRONOMY AND ASTROPHYSICS

A study of bipolar and compact nebulae at radio, submillimetre and infrared wavelengths

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Received February 28, accepted July 29, 1985

Summary. Radio observations have been made of a sample of optically selected bipolar nebulae, to examine their spatial structures and to determine the nature of the sources which excite them. IRAS point source survey data, sub-millimetre wavelength molecular line and continuum measurements have been combined with the radio data to constrain the estimates of the nature of the excitation sources. Two thirds of the sample are found to be associated with luminous ($L > 1000\,L_\odot$) objects which are characteristed as ZAMS B0–B2 stars. Several cases show characteristics of ionised outflowing gas, and may be pre-main sequence objects. The remaining third of the sample have ZAMS exciting stars between B3 and A5.

Key words: bipolar nebulae – H II regions – star formation

1. Introduction

Bipolar nebulae constitute an important class of astrophysical object in which two "lobes" of fan-shaped nebulosity are symmetrically positioned about a central illuminating source. Two categories are recognised to exist: – one class associated with evolved post-main sequence stars (such as CRL 2688, M1–92 and CRL 618), and the second class – the subject of this paper – with embedded young stellar objects (examples are LkH$_\alpha$208, S87, S106, and S146; Neckle and Staude, 1984; Felli and Harten, 1981; Calvert and Cohen, 1978). Until recently the known examples of these nebulae were all optically prominent objects. A survey of POSS plates by Neckle and Staude (1984) revealed 20 new candidate bipolar nebulae lying within ~5 kpc. In order to probe the nature of the exciting sources of these new candidates, and to extend the sample of recognised bipolar nebulae, we have surveyed 12 of them using the Very Large Array[1] to measure their radio structures. IRAS point source catalogue data have been used in conjunction with the radio data to estimate the spectral class of the exciting stars and to show that many of the objects contain substantial amounts of dust. Molecular line and continuum observations of several of the objects have been made at submillimetre wavelengths to test for the presence of any associated neutral gas and dust.

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1 The VLA is operated by the National Radio Astronomy Observatory, on behalf of Associated Universities Inc., under contract with the National Science Foundation

2. The observations

The radio observations were made using the Very Large Array (VLA) on 3 and 4 August 1984, in the compact (1.2 km) *D* configuration. This array was chosen in order to minimise the loss of flux in any large-scale spatial structures around the bipolar nebulae, and to ensure that the field of view was sufficient to extend beyond the optical size of the larger objects. Observations were made at 6, 2, and 1.3 cm, using the 2 channel IF configuration, giving total bandwidths of 100 MHz centred at 4860, 14,940, and 22,460 MHz respectively. A series of short (10–15 min) integrations, interspaced with calibrators, were made for each object, spaced over a range of hour angles, to improve the UV-coverage. Typical integration times were 30–60 min per source. The flux density scale was established by tying the secondary calibrators to 3C286 and 3C84, assuming fluxes of 7.41 and 5.38 Jy respectively at 6 cm, 3.48 and 1.72 Jy at 2 cm, 2.53 and 1.1 Jy at 1.3 cm. Internal consistency of the calibrator data indicated that the flux calibration relative to 3C286 was good to better than 10%.

The data were edited, calibrated and Fourier transformed into maps using the standard VLA reduction programs. In those cases where radio structures were detected, the maps were CLEANed to reduce the effects of sidelobe structure, the CLEAN procedure being iterated to the noise level. All display was carried out using the VLA AIPS data reduction system. The effective maximum angular resolution of the maps was 12″, 4″ and 3″ at 6, 2 and 1.3 cm wavelength respectively.

The infrared energy distributions of the sources have been examined using a composite of the infrared and optical photometry of Neckel and Staude (1984), and data from the IRAS point source catalogue. In addition submillimetre wave molecular line and continuum observations have been made towards several of the objects, using the QMC submillimetre wave spectral line system and the QMC/University of Oregon submillimetre photometer at the United Kingdom Infrared telescope (UKIRT) (White et al., 1981; Ade et al., 1984).

The positions for the bipolar nebulae were taken initially from Table 1 of Neckel and Staude (1984). For clarity in this report, we

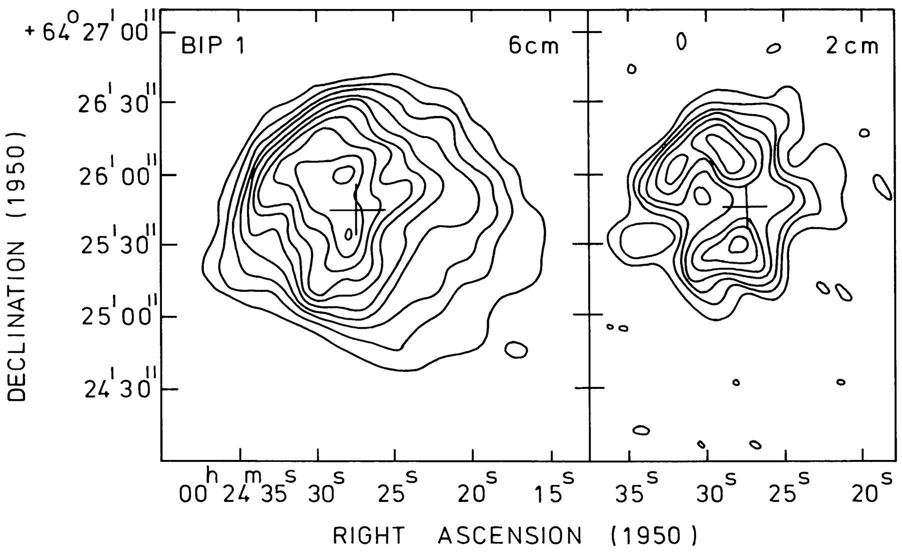

Fig. 1. VLA maps of BIP 1 at 6 and 2 cm wavelength. Both maps have been smoothed to an effective resolution of 15″. The contours are spaced at 0.5 mJy intervals, the lowest contour being at 0.5 mJy. In this and subsequent diagrams a cross marks the position of the near-infrared source reported by Neckel and Staude (1984)

have retained their number system, and we refer to nebula 11, for example, as BIP11. After radio detection, the radio centroids were inspected on the POSS plates using the MANN measuring engine at the VLA. This gave positions repeatable to ~1″.

3. The results

3.1. BIP 1

BIP 1 is the prominent optical nebula known also as S175. It is a diffuse nebula with a diameter of approximately 100″. The exciting star is thought to be an 09.5 star (Georgelin and Georgelin, 1973), obscured by the dust lane which can be seen crossing the nebula. In Fig. 1, VLA maps are shown at 6 and 2 cm wavelength, both of which have been smoothed to an effective resolution of 15″ to facilitate comparison.

At 6 cm the radio structure is sharply bounded to the NE edge, suggesting some confinement of the expansion of the H II region in this direction. The radio structure is more diffuse to the SW, where it falls to the noise level by about 90″ from the centre of the radio structure. The overall dimensions of the radio-emitting region are ~2.′2 × 2′, rather similar to that of the optical distribution. At 2 cm wavelength the structure of the nebular seems slightly bifurcated, suggesting that this object may appear as a true bipolar source at radio wavelengths, as seen in the case of S106 (Bally et al., 1983). However given the limited U–V coverage and the large diameter of this source, it is clear that the present data alone are inadequate to be certain of the radio bipolarity, and further observations are desirable to settle the case for this source. We note that the bifurcated radio structure is aligned in the same general direction as that of the optical "lobes" seen in Neckel and Staude's work. The integrated flux from the nebula at 6 cm is 113 mJy. If it is assumed that the nebula is fully ionised, and lies at a distance of 2.3 kpc (Georgelin and Georgelin, 1973), then the production rate of Lyman continuum photons can be estimated from the integrated 6 cm flux density (Schraml and Mezger, 1969; Panagia, 1973; Thompson, 1984). For the observed integrated 6 cm radio flux, the observations would indicate a ZAMS exciting star of spectral class B 0.5 ar later. For this we assume that the radio emission comes from an optically thin plasma for which the rate of emission of ionising photons, N, can be estimated from the equations given by Schraml and Mezger (1969).

$$N \sim 9\ 10^{43} \left(\frac{S_\nu}{\mathrm{mJy}}\right) \left(\frac{D}{\mathrm{kpx}}\right)^2 \left(\frac{\nu}{4.9\ \mathrm{GHz}}\right)^{0.1} \mathrm{s}^{-1}$$

where S_ν is the integrated flux density in mJy, D is the distance in kpc and ν is the observing frequency. This relationship will be adopted throughout this paper as a guide to the Lyman continuum rate of the exciting sources unless otherwise stated. The relationship assumes that contributions to the observed radio flux at a wavelength of 6 cm are not dominated by shock ionisation, the continuum emission of compact ionised wind sources in the H II region or Balmer continuum ionisation of excited atoms. A general way to discriminate between optically thin plasma, optically thick plasma, or ionised stellar winds is to measure the radio spectral index. This will be ~ −0.1, +2, and +0.6 respectively for the three cases above (Rodriguez and Canto, 1983).

The 100, 60, 25, and 12 micron fluxes from the IRAS point source data base have been examined at the position of BIP 1, and in Fig. 2 we show a composite spectrum combining the IRAS, radio, near-IR and optical data from this work and the Neckel and Staude study. This diagram contains composite spectra for all the objects for which VLA data were obtained. Typical absolute errors in the IRAS data may be up to 70 % at 100 microns and 40 % at 60 microns (IRAS Catalogue Explantory Supplement – depending on the galactic location of the source).

The integrated infrared flux between wavelengths of 1 to 100 microns is consistent with an exciting source of ~2000 $L_\odot$, corresponding to a ZAMS star of spectral class B 1–B 2. In order to estimate the luminosieties from the IRAS point source catalogue data, it is necessary to make a first-order correction to the various IRAS fluxes to account for intrinsic source spectrum. Colour-Colour plots were constructed from the IRAS data to form an estimate of the temperature of the emitting dust. On the basis of these plots we have arbitrarily adopted two blackbody temperatures of 100 K and 200 K as representative of the infrared spectra of the objects. For BIP numbers 4, 5, 6, 12, 13, and 19 we adopt the higher temperature, and for the remaining objects, the lower. The colour corrections used make only *small* modifications to the estimated luminosities (less than 20 %) and are always insufficient

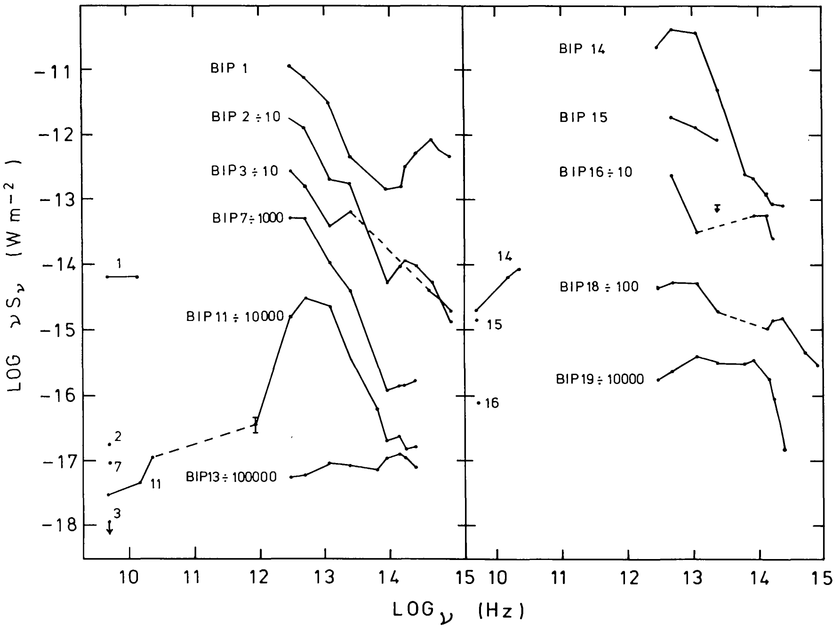

Fig. 2. Composite spectra of the sample of bipolar nebula. The near infrared points are taken from Neckel and Staude (1984) the mid- and far-infrared points from the IRAS point source catalogue, and the radio wavelength data from the integrated VLA fluxes from the present work

to modify significantly the spectral classes determined for ZAMS stars. Thus, the radio and IRAS data would exclude the exciting star from being earlier than B 0.5. For dust temperatures of 75-several hundred K, at least 80 % of the total luminosity is emitted between ~10 and 100 microns wavelength, we thus take the IR luminosity determined from IRAS data as giving the bolometric luminosity to better than a factor of two. For BIP 11, the only source for which we have submillimetre continuum data, the luminosity determined from the IRAS and near infrared data is ~15 % less than the bolometric luminosity determined when the submillimetre point is included. At 2 cm wavelength, two peaks are seen separated by approximately 30″ in a north-south direction, as shown in Fig. 1. The nebula is less extended to the SW. The integrated intensity in the 2 cm map is 42 mJy after correction for the primary beam response of the VLA dishes. This is somewhat lower by a factor of ~2 than would be expected for ionised optically thin gas, and may be due to an underestimation of the integrated flux, a consequence of the lack of short spacings and incomplete UV-coverage of the VLA, for this very extended object.

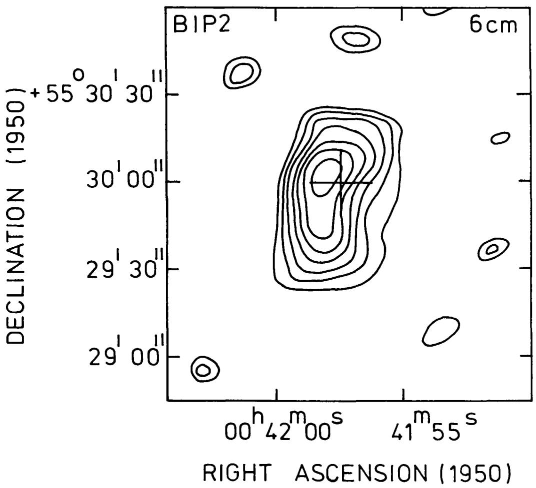

Fig. 3. VLA map at 6 cm wavelength of BIP 2b. The map has been smoothed to a resolution of 20″ to show the weak emission extended N–S. The lowest contour is at 0.3 mJy per beam, with the contour interval being 0.1 mJy per beam

3.2. BIP 2

This object consists of several clumps of optical emission spread over an area of about 4 square arc minutes. The two brighter optical clumps are designated as objects 2a and 2b by Neckel and Staude (1984), who associate both clumps with B5 ZAMS exciting stars lying at a distance of 1.7 kpc. The 6 cm map of the area is shown in Fig. 3. Emission was only detected from BIP 2b.

The radio distribution is extended N–S, and is unresolved E–W. The peak radio position lies within a quarter beamwidth ~5″ of a faint stellar object visible on the POSS plates, coincident with the infrared source detected by Neckel and Staude (1984). The optical nebulosity extends southwards of this point, no optical emission being seen in the nothern area of the radio map. However, we caution that the radio data have been heavily smoothed, and that further high signal to noise data will be required to compare the optical and radio distributions more accurately. The peak flux corresponds to 0.9 mJy per beam, and the integrated flux is 3.5 mJy. Assuming optically thin ionised gas, this radio flux would imply an exciting star of ZAMS class B1–B2.

The IRAS data are consistent with an infrared luminosity determined between (1 and 100 microns) of 1.2 $10^3\ L_\odot$, and would imply a B2–B3 exciting star, in good agreement with the radio estimate. An infrated excess may be present between 3 and 12 microns, indicating the presence of hot dust grains as seen in Fig. 2.

Observations of BIP 2a failed to show any emission greater than 0.3 mJy per beam. A strong point source was found close to the edge of the VLA map field with a flux (corrected for primary beam response) of 9.1 mJy at RA (1950) = $00^h41^m28^s.4$, Declination (1950) = +55°29′50″.7. This point source lies 31″ S and 7″ W of a faint stellar object surrounded by a patch of diffuse nebulosity. It is possible that the radio object may be an unrelated background extragalactic source. Inspection of the IRAS point source catalogue showed no possible infrared identifications with this object.

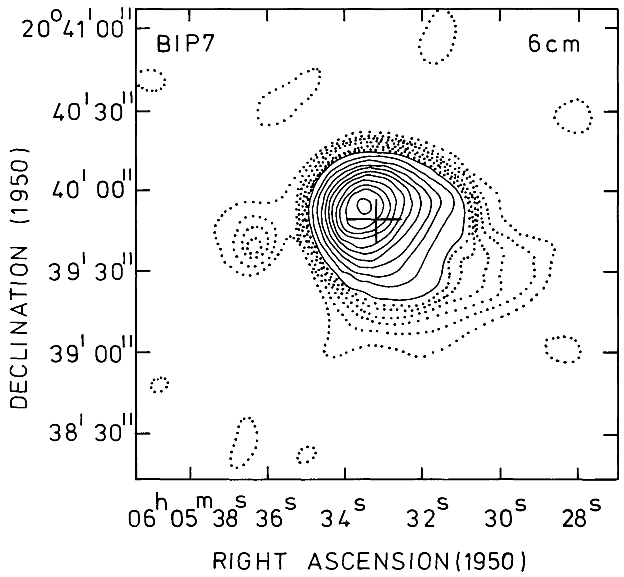

Fig. 4. VLA map at 6 cm wavelength of BIP 7. To display the full dynamic range, the data are drawn on two different contour intervals; the dotted contours have a minimum value of 0.6 mJy per beam, increasing at intervals of 0.6 mJy; the solid contours have a minimum value of 4 mJy per beam, increasing at intervals of 2 mJy per beam. The angular resolution is 12″

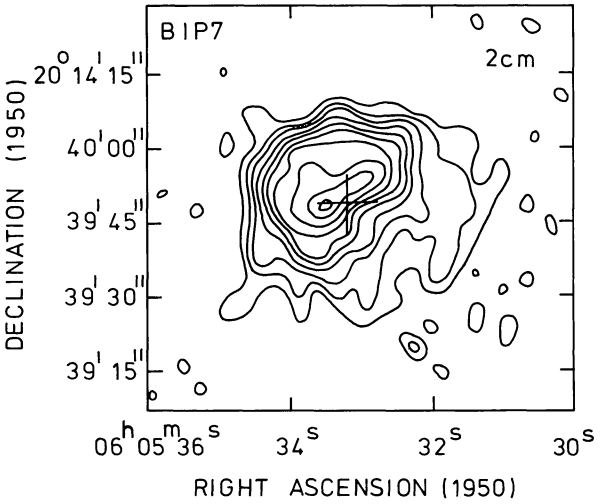

Fig. 5. 2 cm wavelength map of the central region of BIP 7. The lowest contour is at 0.5 mJy per beam, with successive increments of 0.5 mJy per beam. The data have been smoothed to a resolution of 6″

3.3. BIP 3

This is a faint, cometary, reflection nebula, also known as Cohen 6 (Cohen, 1980). VLA observations at 6 cm failed to detect any emission from either the optical nebulosity of from the infrared source reported by Neckel and Staude (1984), setting an rms upper limit of 0.21 mJy per beam. This would imply a spectral class later than B2, assuming a distance of 5.5 kpc (Neckel and Staude, 1984). The IRAS point source catalogue data are shown in Fig. 2. The lack of near infrared results make the derivation of luminosity somewhat uncertain, but the IRAS data probably would imply a luminosity $\sim 2.2\ 10^3\ L_\odot$, consistent with the suggestion of Neckel and Staude of a B2V star. A radio detection would be expected at or close to our noise level.

A point radio source was present in the 6 cm map lying about 80″ away from the apex of BIP 3. The flux density was 1.1 mJy at RA (1950) = $02^h13^m09^s.0$, DEC (1950) = +50°08′01″. This corresponds to a blank field on the POSS blue plate.

3.4. BIP 7

This object is a small diameter (~70″) H II region. Neckel and Staude (1984) suggest that the ionising star is an 09.5 star embedded in the nebula, suffering an extinction $A_v = 9.9$ mag. This estimate assumes BIP 7 to be associated with the nearby H II region S252, lying at a distance of 2.3 kpc. The VLA 6 cm map of this object is shown in Fig. 4.

The core of BIP 7 is dominated by a spherical region of diameter ~35″ (uncorrected for the synthesised beam size). Surrounding this is diffuse emission which extends some 75″ to the SW, although it is not extended to the NE. To the east of the main radio peak, a second source is seen which is separated by ~40″. The bulk of the radio flux however comes from the main H II region. The total integrated emission of this main peak is 198 mJy. For an optically thin nebula at 2.3 kpc, this would correspond to an exciting star of class B0–B0.5. The eastern component is centred at RA (1950) = $06^h05^m36^s.0$ DEC (1950) = +20°39′40″, and has a peak flux of 2.7 mJy per beam, at 6 cm, and 1.5 mJy per beam (4″ FWHM) at 2 cm. The integrated intensities are 4.7 and 1.6 mJy at 6 and 2 cm respectively. It is unclear whether this object is associated with BIP 7, although from its spectrum, it seems likely that this may be a non-thermal, possibly extragalactic, source lying in the same direction as BIP 7.

The structure of BIP 7 was also mapped with the VLA at 2 cm wavelength, and the map is shown in Fig. 5.

The 2 cm map shows the core region to have a diameter of approximately 25″ (uncorrected for beam size), with a weak SW extension as also seen in the 6 cm map. The Neckel and Staude (1984) infrared source lies to the SW of the radio centroid by ~1 synthesised 2 cm beamwidth. The total flux at 2 cm wavelength for BIP 7 is 71 mJy.

The IRAS and infrared data are shown in Fig. 2, and indicate a luminosity of $\sim 9.8\ 10^3\ L_\odot$. These results are consistent with an exciting star of spectral class B0–B0.5, in good agreement with that estimated assuming that the 6 cm emission comes from optically thin ionised gas.

3.5. BIP 11

This object is seen as an extended (~60″ diameter) optical nebula seen to have a very sharp SW edge, possibly as the result of dust absorption of the nebular emission. Neckel and Staude estimate from optical photometry and spectroscopy, that the exciting star may be as early as 07. The VLA data show BIP 11 to be a strong radio source, and maps were made at 6, 2, and 1.3 cm. At 6 cm, the structure of the object was only marginally resolved by the 12 arcsec beam. The total integrated flux was 605 mJy and the peak flux was 357 mJy per beam. The higher angular resolution achieved at 2 and 1.3 cm was sufficient to resolve the structure of BIP 11 as shown in Fig. 6.

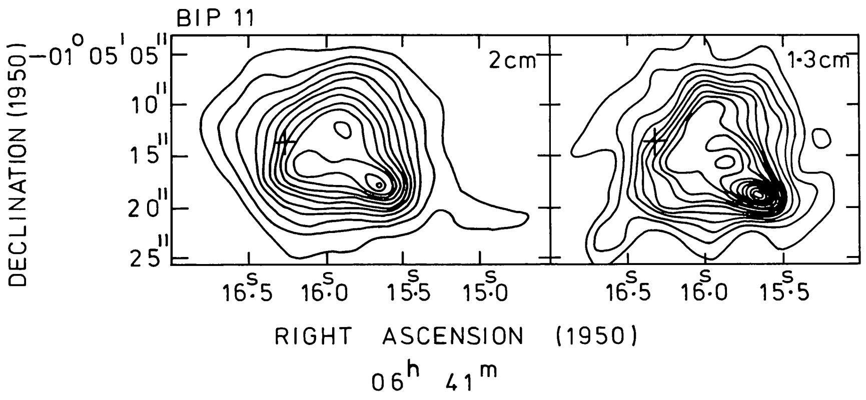

Fig. 6. VLA maps at 2 and 1.3 cm wavelength of BIP 11. Both maps have been smoothed to an angular resolution of 4″ for comparison. The lowest contour is 3 mJy per beam with contour increments of 3 mJy per beam

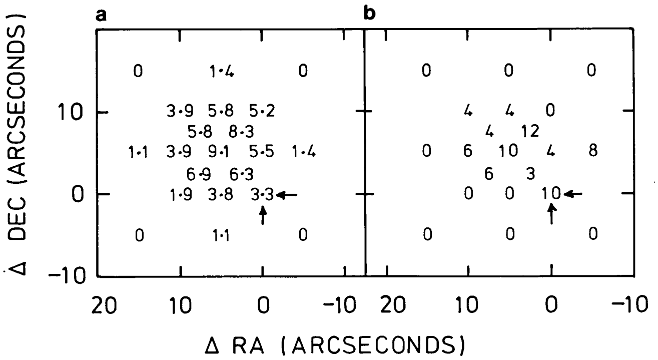

Fig. 7. **a** Measurements of Brackett-α line intensity obtained with the cooled grating spectrometer at UKIRT, with a spectral resolution of 0.007 microns ($500\,\mathrm{km\,s^{-1}}$). The line fluxes are in units of $10^{-20}\,\mathrm{W\,cm^{-2}}$, the statistical uncertainty is $0.3\ 10^{-20}\,\mathrm{W\,cm^{-2}}$ and the aperture size 5″. **b** Measurements of the continuum flux determined from channels in the CGS spectrum lying away from the line. The units are $10^{-19}\,\mathrm{W\,cm^{-2}\,\mu m^{-1}}$, and the statistical uncertainty is $2\ 10^{-19}\,\mathrm{W\,cm^{-2}\,\mu m^{-1}}$

In both maps shown in Fig. 6, the source is resolved into a compact component in the SW, and a fan-shaped region of more diffuse emission extending about 10″ NE of the compact component. The Neckel and Staude (1984) candidate exciting star lies at the far edge of the diffuse region. The total integrated emission is 307 mJy at 2 cm wavelength rising to 500 mJy at 1.3 cm wavelength. The rise is associated with the spectral variation of the compact component. The spectral index of emission indicates $S_\nu \propto \nu^{0.6^{-0.1}_{+0.2}}$, after making first order corrections for the contribution of the extended diffuse emission. Refinement of this spectral index will require further higher angular resolution data. However the radio data are consistent with spectral indices obtained towards a number of young stellar objects buried in molecular clouds (Simon et al., 1983), where spectral indices in the range of 0.6 – 1.0 are interpreted as indicating the presence of outflowing circumstellar ionised envelopes.

In order to examine further the structure of BIP 11, Dr. Tom Geballe of UKIRT kindly obtained a map of the central region region of this object in the Brackett-α recombination line and 4 μm continuum, which he has kindly allowed us to publish here. The Brackett-α emission is seen to peak close to, but not coincident with the compact source. There is a possible weak 4 μ continuum source (5σ detection) which lies coincident with the compact radio source.

We calculated the expected Brackett-α line flux from the compact source following the theory derived by Krolik and Smith (1981) and Simon et al. (1983). The observed Brackett-α line flux at the position of the compact object is consistent, to within conservative uncertainties, with that expected from an optically thin compact H II region, but is much weaker (by almost two orders of magnitude) then that which would be expected for an optically thick ionised wind model. Thus contrary to the expectation based on the radio spectral index, the true nature of the compact source in BIP 11 remains unclear.

The region where Brackett-line emission is strong lies coincident with the patch of extended radio and optical nebulosity. Applying the standard relationship from Krolik and Smith (1981) which relates the optically thin Brackett-α and 5 GHz radio continuum fluxes by

$$I(\text{Brackett-}\alpha) = 2.6\ 10^{-21}\, S_{5\,\mathrm{GHz}},$$

where I is in units of $\mathrm{W\,cm^{-2}}$ and S is in mJy, we predict $I(\text{Brackett-}\alpha) = 1.5\ 10^{-18}\,\mathrm{W\,cm^{-2}}$. To compare with this estimate we have integrated 6 cm ratio flux (minus 20 mJy to allow for the compact component to represent the H II region flux). The *integrated* line emission of $8\ 10^{-19}\,\mathrm{W\,cm^{-2}}$ thus compares to within a factor of two with that predicted from the above relationship for an optically thin H II region. Allowing for extinction, the results would imply a value of $Av < 20$ mag, although the precise value of this extinction estimate is poorly determined based solely on the present results.

At 6 cm the contribution of the point source to the integrated flux is small; and assuming it to be the exciting source of BIP 11, rather than the Neckel and Staude candidate, then the 6 cm flux (dominated by the free-free nebular emission) would be consistent with a star of spectral class B0.5 – B1. This agrees well with the IRAS and near infrared luminosity which is $\sim 2800\,L_\odot$, consistent with a B2 ZAMS star, assuming the distance to the source to be 1.4 kpc (Neckel and Staude, 1984).

The position of the compact radio peak lies exactly at the edge of the sharply bounded optical rim of the nebula which can be seen on the POSS red plate. The distribution of optical radiation seen on the POSS plate is similar to that of the radio lobe, extending to the NE. No optical emission is visible to the SW of the compact radio centroid. It remains unclear whether the Neckel and Staude (1984) cadidate star is the true exciting star for the nebular, on the basis of the radio and IRAS data, it would appear more likely to be an object associated with the point radio component.

In order to examine whether this source has associated molecular material and dust, we have carried out CO $J = 3 - 2$ measurements and 350 micron wavelength photometry. In the CO data, a weak line is present with $T_R^* = 1.7 \pm 0.4$ K at an LSR velocity of $+17.5\,\mathrm{km\,s^{-1}}$, and with a linewidth of $8.7\,\mathrm{km\,s^{-1}}$. This velocity corresponds to that which would be expected based on standard rotation curves for the galaxy, for a molecular cloud at the correct distance of 1.4 kpc. The line is much weaker than that which might be expected from a typical molecular cloud associated with a star formation region, which uniformly filled the telescope beam. Thus assuming the CO emission to be associated with BIP 11, then either the molecules are not strongly heated by the bipolar source, or the molecular emission originates in a compact region (such as a circumstellar disc?) of unknown size.

A measurement of the flux at 350 microns wavelength towards BIP 11 resulted in a detection with an integrated intensity of 42 ± 10 Jy (the error bars are ± 1 sigma). This data point has been incorporated into the composite spectrum shown in Fig. 2. The 350 micron point can be modelled with the IRAS data to estimate the dust temperature, assuming emission from an isothermal sphere which is optically thick at the peak of the far-infrared spectrum (as estimated for some other embedded objects – see for example Tokunaga et al., 1978). Acceptable fits to the 25–350 micron data were only found for a blackbody temperature of 80 K with an uncertainty of about 10%. This estimate assumes a grain emissivity $\propto \nu$. This would indicate the optical depth of the dust to be unity at 96 microns wavelength, and that the diameter of the emitting region is 2″.2. The infrared excess at ~ 3 microns seen in Fig. 2 represents stellar continuum, and a better modelling of the data would require a more complex treatment of the radiative transfer which is beyond the scope of the present work. If the dust at $T_K \sim 75-100$ K is mixed with molecular material, then we can use the molecular line intensity to set an upper limit for the size of the emitting region at 45 square arc seconds. The presence of compact ionised and neutral cores in late-type bipolar nebulae has already been proposed based on molecular hydrogen measurements (Phillips et al., 1983, 1985), and thus the above argument is not unreasonable considering the many similarities between some late type bipolar nebulae, and early type bipolars, and awaits higher angular resolution molecular line measurements.

3.6. *BIP 13*

This object appears on the POSS plates as a fan-shaped nebula (also known as Pismis 17) lying in a dust cloud. Neckel and Staude estimate the exciting star to be of spectral class B9 lying at a distance of 350 pc. Observations with the VLA at 6 cm wavelength failed to detect any emission greater than an rms of 0.2 mJy lying anywhere within a 1 square arcminute box centred on the Neckel and Staude (1984) position. A strong point source was found to be at RA (1950) = $06^h55^m31\overset{s}{.}7$, Dec (1950) = $-07°50'09''$, with a flux density of 46.2 mJy. This may be an extragalactic field source. Inspection of the IRAS point source catalogue indicated no infrared object at this position. The failure to detect a source at the position of BIP 13 is consistent with excitation by a ZAMS star later than $\sim$B3.

The IRAS and infrared data indicate a luminosity of about $5\,L_\odot$. The infrared spectral distribution shows a very substantial mid-infrared excess, indicating the presence of a range of dust grain temperatures. The low luminosity and lack of radio emission point to this being a low-mass evolved region, and it seems unlikely that it is an object excited by an early-type star.

3.7. *BIP 14*

Three distinct nebulous patches are visible on the POSS red plate associated with this object, the area between the two most easterly objects being cut across by what appears to be a sharp edged dust lane. Neckel and Staude find one (and possibly two) infrared sources at the centre of the dust lane and on the basis of their infrared photometry assign a distance of 1.4 kpc. An optical spectrum of the nebulosity was consistent with low excitation gas excited by a star of spectral class B0 or later. VLA maps were made at 6, 2, and 1.3 cm. The 6 and 2 cm maps show a compact, unresolved point source. This object is just marginally resolved at 1.3 cm. The peak radio position lies at RA (1950) = $06^h56^m46\overset{s}{.}3$ Dec (1950) = $-03°55'25''$. The integrated emission at 6, 2, and 1.3 cm wavelength was measured to be 40.9, 44.5, and 39.2 mJy respectively. The fluxes are consistent (to within the absolute calibration errors) with a flux falling as $\nu^{-0.1}$, indicative of a relatively flat spectrum. This suggests that an optically thin, uniform density H II region rather than an ionised stellar wind, is responsible for the emission. From the 1.3 cm data, we estimate the source size to be $< 2''$. The radio flux is consistent with the presence of a B0.5 – B1 ZAMS star. Taking the size estimate, we can estimate lower limits of the average electron density of $1.5\;10^4\,\mathrm{cm^{-3}}$ and the emission measure $3.7\;10^4\,\mathrm{cm^6\,pc^{-1}}$, following the equations of Schraml and Mezger (1969).

The IRAS data indicate the luminosity to be $\sim 5.1\;10^3\,L_\odot$, consistent with a B0.5–B1 star. Taking the radio derived emission measure, and the luminosity we have found, we can position the BIP 14 on a $\log(L/L_\odot)$ versus $\log(\mathrm{Ne^2V})$ curve (Thompson et al., 1983), where it is found that the radio measurements agree well with the predictions for ZAMS star (Panagia, 1973; Thompson, 1984), but *exclude* the, exciting source of BIP 14 from lying in the part of the diagram where line excess objects (Thompson, 1982) are found. These are objects which are associated with mass loss and ionised flows, but which may not yet have reached, or settled down into the main sequence. Finally, the Stromgren radius for a B0.5–B1 star at 1.4 kpc is $\sim 3\;10^{16}$ cm, corresponding to a projected size of 3″, reasonably consistent with the estimated source size, given the beam sizes we have used.

The available data for BIP 14 are entirely consistent with the presence of a central B0.5–B1 star surrounded by an H II region. It is unclear whether the optical structure of the associated nebulosity represents a flow source, or if local foreground extinction just gives the appearance of a bipolar source.

The radio peak was positioned on the optical image of the POSS plates, and found to coincide with the centre of the dust lane. We note that there is a separation of 15″ between the position quoted for the infrared source by Neckel and Staude, and the radio derived position. The radio positions at all frequencies agree with each other, and with the IRAS position, thus the association of the Neckel and Staude infrared source and the radio/IRAS source are not consistent.

Finally a second radio source was present in the 6 cm wavelength map at RA (1950) $06^h56^m59\overset{s}{.}5$ Dec (1950) = $-03°57'07''$ with a flux corrected for primary beam response of 12.3 mJy. This is probably an extragalactic field source. No associated infrared source was found in the IRAS point source catalogue.

3.8. *BIP 15*

This is an extended optical nebulosity lying very close to S29. Assuming it is associated with S29, then the distance will be 1.3 kpc (Blitz et al., 1982). The VLA map at 6 cm is shown in Fig. 8.

The radio structure is seen to be resolved into at least 3 separate regions, two intense peaks lying in the central region of the object, and separated by $\sim 20''$ from each other, and a third peak lying $\sim 30''$ to the north of these two. There also may be a fourth (weak)

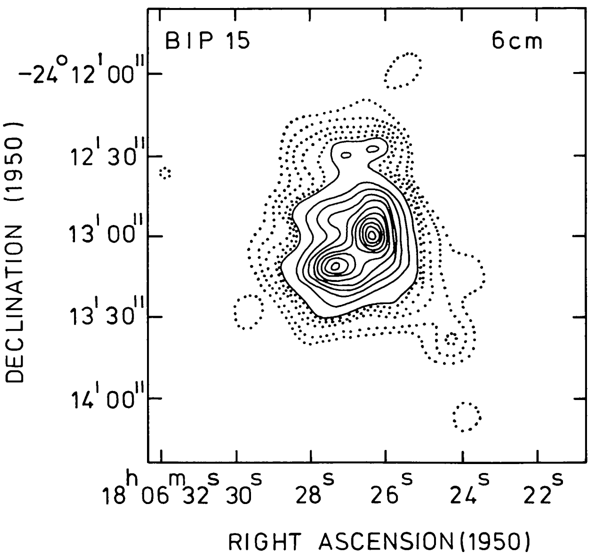

Fig. 8. 6 cm wavelength VLA map of BIP 15. The lowest dotted contour corresponds to 0.05 mJy per beam, increasing at intervals of 1.0 mJy per beam, the lowest solid contour is at 5 mJy per beam, increasing at intervals of 5 mJy per beam. The angular resolution is 12″

peak lying ~50″ SW. No infrared source was observed towards BIP 15 by Neckel and Staude (1984). The total integrated radio flux corresponds to the presence of one (or two) ionising star(s) of spectral class B0–B0.5. The two main peaks are at positions of; peak 1, RA (1950) $18^h06^m26\overset{s}{.}4$, Dec (1950) −24°12′58″, with a peak flux of 61 mJy per beam, and peak 2, RA (1950) $18^h06^m27\overset{s}{.}3$, Dec (1950) −24°13′12″ with a peak flux of 51 mJy per beam. The total integrated flux within the whole map is 330 mJy, of which 27 mJy is associated with the northermost of the four peaks, and 2 mJy with the weak south western extension. Peak 1 is coincident with a bright knot of optical emission on the ESO blue plate, whereas peak 2 is associated with very weak optical emission on the blue plate. The whole area is heavily saturated on the POSS red plate.

The IRAS results shown in Fig. 2 are only available to wavelengths of 60 microns, the 100 micron point suffering from confusion effects. The mid-IR IRAS data (12–60 microns) correspond to a luminosity $>130\,L_\odot$. With the 100 micron point, the total luminosity may be $>200\,L_\odot$. These values are about an order of magnitude lower than that expected if 1 or 2 B0–B0.5 stars are present, and it will be necessary to examine in detail the IRAS sky flux maps (as opposed to the point source catalogue) fo form a good estimate of the total IR luminosity.

A CO $J=3-2$ spectrum was obtained at UKIRT towards BIP 15. Two CO lines were detected having $T_R^*=5$ K at $V_{\rm lsr}=+51$ km s^{-1} and $\Delta v=3$ km s^{-1}, and a second line width $T_R^*=4$ K, $V_{\rm lsr}=+2$ km s^{-1} and $\Delta v=2$ km s^{-1}. The +51 km s^{-1} line must originate from material lying >10 kpc from the Sun, and is unlikely to have an associated optically visible object. The +2 km s^{-1} line probably originates from material lying within 1–2 kpc, and thus may be associated with BIP 15.

3.9. *BIP 16*

This resembles a compact optical nebula. Neckel and Staude are unable to assign an unique spectral class to this the object. The source was observed with the VLA at 6 and 2 cm wavelength. The source was barely resolved at 6 cm, having a peak flux of 33 mJy per beam, and an integrated flux of 36 mJy. At 2 cm wavelength we detect a compact core of diameter < 4″ with an integrated flux of 19 mJy. The radio peak is centred in the middle of the optical nebulosity.

The IRAS point source catalogue data are shown in Fig. 2. There is a strong near-infrared excess, and the overall infrared distribution corresponds to a luminosity $>100\,(D/{\rm kpc})^2\,L_\odot$, where D is the distance expressed in kpc (the distance to this object is unknown). The radio data imply a star of spectral class B1 at 1 kpc, or B0.5 at 2 kpc. For a B1 ZAMS star we would expect the total luminosity to be $\sim 5000\,L_\odot$. No reasonable solution for both the IR and radio luminosities can be found, and it would seem that the radio flux is much higher than expected on the basis of the IRAS luminosity. However since no IRAS 100 micron data are available (the upper limit is 349 mJy), it is not possible to draw any useful conclusions.

3.10. *BIP 18*

This is a bright cometary nebula, for which Neckel and Staude estimate the exciting source to be an A5 star at a distance of 400 pc. No 6 cm radio emission was detected to an rms upper limit of 160 microjanskys per beam at the position of the infrared source.

The IRAS data suggest a total luminosity of $\sim 6\,L_\odot$ consistent with an A5−F0 star. There is a strong mid-infrared excess, indicating a number of different dust temperatures to be present. BIP 18 would thus seem to be associated with a low mass star, and represents one of the class of bipolar nebulae associated with a low mass star, and represents one of the class of bipolar nebulae associated with an evolved star, or a reflection nebula or possibly a T Tauri like object.

Two weak compact radio sources (presumably extragalactic) are seen in the 6 cm field, their parameters are; source 1; RA (1950) $19^h26^m21\overset{s}{.}9$ Dec (1950) +09°31′08″, with a flux density (corrected for primary beam attenuation) of 1.6 mJy, and source 2; RA (1950) $19^h26^m36\overset{s}{.}9$ Dec (1950) = +09°33′17″ with a flux density of 0.75 mJy. Both objects correspond to blank fields on the POSS plates and have no associated infrared emission in the IRAS point source catalogue.

3.11. *BIP 19*

This appears as a wisp of reflection nebulosity lying close to the peculiar pre-main sequence object PV Cephei (Cohen et al., 1977). A molecular flow source (Leverault, 1984) has been discovered close to the reflection nebula. No radio flux was detected at 6 cm wavelength within a region of diameter 4′ around his object, to an upper limit of 180 microjansky per beam. This is similar to the upper limit determined by Cohen et al. (1982), and confirms the apparent discrepancy noted by Leverault (1984) between the mass loss rates determined from radio continuum measurements and those estimated from the neutral molecular flows. The IRAS spectrum is shown in Fig. 2, and by integrating the 12–100 micron data at the BIP 19 position the luminosity is $\sim 40\,L_\odot$. This is only slightly lower than the luminosity reported by Leverault (1984) quoting a private communication from B.A. Wilking (1983). There is a substantial mid and near infrared excess indicating the presence of warm dust grains.

3.12. *BIP 20*

This object appears optically as a prominent bipolar nebula lying ~3′ to the south of the optical nebula NGC 7129. Neckel and

Table 1. Summary of VLA and IRAS observations

BIP	VLA position (1950) RA (h m s)	VLA position (1950) Dec (° ′ ″)	IRAS position (1950) RA (h m s)	IRAS position (1950) Dec (° ′ ″)	6 cm integrated flux (mJy)	Radio spectral class	IR luminosity ($L_\odot$)	IR spec class
1	See map		00 24 28.0	+64 25 41	113	B0.5	1990	B2
2b	00 41 57.8	+55 30 05	00 42 05.4	+55 30 54	3.5	B1–B2	1180	B2–B3
3	Not detected		02 13 03.3	+55 09 12	< 0.21	–	2240	B2
7	06 05 33.5	+20 39 49	06 05 33.9	+20 39 47	198	B0–B0.5	9800	B0.5
11	06 41 15.6	−01 05 19	06 41 12.5	−01 05 02	605	B0.5–B1	2870	B2
13	Not detected		06 55 37.4	−07 52 39	< 0.22	Later than B3	5	F0
14	06 56 46.5	−03 55 25	06 56 46.5	−03 55 28	41	B0.5–B1	5141	B1
15	See map		18 06 26.8	−24 13 09	330	See text	$156<L<270$	See text
16	18 29 55.7	−10 08 07	18 29 55.7	−10 08 22	36	See text	See text	See text
18	Not detected		19 26 37.8	+09 32 31	< 0.16	Later than F5	6	A5–F0
19	Not detected		20 45 23.6	+67 46 36	< 0.18	–	48	B9
20	Not detected		Confused		–	–	Confused area	–

Staude (1984) failed to detect near infrared radiation from BIP 20, although several 2 micron sources lie nearby (Strom et al., 1976). NGC 7129 itself is a large star formation complex, containing molecular flows and embedded objects (Bechis et al., 1978; Edwards and Snell, 1983; Avery et al., 1985; Sandell and Liseau, 1985).

A radio map was obtained at 6 cm towards BIP 20, the field of view also covering NGC 7129 and the Herbig-Haro objects HH 103 and GGD-32. An rms upper limit of 0.15 mJy per beam was found for the position of BIP 20, implying, for a distance of 1 kpc (Racine, 1968), that the ZAMS spectral class of the illuminating star is later than B4. Recent optical polarization data (Draper et al., 1985) indicate the central exciting source to lie projected behind the southern lobe of the visible nebulosity, and they suggest that it may be a T-Tauri star which is hidden from view by a dense dust torus.

The IRAS point source catalogue data for this region suffer strongly from confusion effects, and cannot be used with reliability at the position of BIP 20. Far infrared data have been presented by Harvey et al. (1984) for the NGC 7129 complex, who show that a 50 micron source lies about 1′ south, but not coincident with BIP 20. It would therefore seem that BIP 20 does not, unlike the other BIP objects studied here, have a luminous central object, and it may represent a reflection nebula from one of the other infrared sources in the vicinity.

Two point like radio sources are detected in the VLA map, which are coincident with LkH$_\alpha$234 and BD +65°1638. The radio position for the LkH$_\alpha$234 source was measured to be RA (1950) = 21^{h}41^{m}57^s.4, Dec (1950) = +65°53′08″, with a flux density (corrected for primary beam response) of 1.46 mJy. This value can be used with the 23 GHz measurement of Bertout and Thum (1982) to estimate the spectral index, α, of the radio emission, $S \propto \nu^\alpha$, to be $0.9 < \alpha < 1.3$ (assuming that the source has not varied between 1980 and 1984, and also that confusion with the nearby, but weaker radio source associated with BD +65° 1638 has not contaminated the 23 GHz data. If this latter case is true it will have the effect of decreasing the spectral index). It would thus seem that LkH$_\alpha$234 has a radio continuum slope only just greater than the $\alpha = 0.6$ slope expected for a consistent velocity outflow with the electron density varying as r^{-2}. Higher angular resolution single epoch measurements will be needed for LkH$_\alpha$234 if more quantitative modelling is required, and to determine if this outflow is connected with the more extended molecular outflow. Based on the luminosity estimate of Harvey et al. (1984) who estimate that LkH$_\alpha$234 is a B3 star (from far infrared measurements) or a B0 star (from near infrared measurements), we can estimate the 5 GHz flux predicted for free free emission (which probably dominates the radio flux at this frequecy). The respective estimated fluxes are ~2 Jy and 0.35 mJy. Neither estimate agrees exactly with the VLA data, but we can rule out the presence of a B0 star. It would seem likely in this case that LkH$_\alpha$234 is a pre-main sequence object.

Table 2. Luminosities and estimated spectral classes for other bipolar nebulae from the Neckel and Staude sample

BIP no.	Luminosity $L_\odot$	Spectral class
4	8.8	A5
5	93.5	B8
6	No IRAS detection	
8	5650	B1
9	No IRAS detection	
10	No IRAS detection	
12	21.8	A1
17	No IRAS detection	

The other exciting source of NGC 7129 is the star BD +65° 1638. A compact radio peak was detected lying within 4″ of the optical star, at coordinates of RA (1950) 21^{h}41^{m}47^s.4 Dec (1950) = +65°52′25″. The flux density was 0.99 mJy. The near and far infrared photometry of Harvey et al. (1984) suggest that this is ZAMS star of class B2. The predicted radio flux is in excellent agreement with that expected from a B2 star surrounded by an ionised gas shere (~2 mJy).

Towards the positions of the Herbig-Haro objects HH 103 and GGD 32, rms upper limits of 0.5 mJy per beam can be set.

The data for the bipolar nebulae observed with the VLA are summarised in Table 1. The positional uncertainty of the IRAS data is generally ~15–30″.

3.13. *Other BIP objects*

The IRAS point source catalogue has been examined at the positions of the other bipolar nebulae listed in the Neckel and

Staude survey. In Table 2 the luminosities and estimated ZAMS spectral types for the excitung stars are listed. In some cases failure to detect the objects with IRAS may be a result of confusion by nearby sources.

4. Comments and summary

The present survey has detected radio emission from eight of the twelve bipolar nebular selected from the Neckel and Staude (1984) survey for optical bipolar nebulae. BIP number 1, 2, 3, 7, 11, and 14 are associated with luminous far infrared sources and are probably excited by stars of spectral class B2 or earlier, BIP 13, 18, 19, 20 are probably excited by stars with a spectral class later than B3, and in the cases BIP 18 and 19, are probably late type A stars.

The radio spectra towards several of the sources detected in the survey, BIP 11 and $LkH_\alpha 234$ have indications of outflowing stellar winds. In BIP 11, the diffuse radio lobe surrounding the point object may show the outflow to be anisotropic, possibly bounded by a molecular cloud and $LkH_\alpha 234$ may have a large, collimated molecular outflow associated with it.

The selection criteria for the present sample was based on the bipolar optical appearance of the nebulae on the POSS. It is therefore disappointing that few of these objects show radio characteristics more similar to those of the archetypal bipolar nebula S106 (Bally et al., 1983). Of our sample, only BIP 1, 2 and possibly 15 show any hint of bifurcated structures, and BIP 11 may possibly be a "monopolar" source. In contrast, objects such as BIP 14 or 20, which have very clear optical bipolar structures, have in the former case, a point like radio structure, and in the latter case, no detectable emission. It is clear that the few objects like S106 are rather special cases of the bipolar phenomenon.

In several cases, the total luminosity of the nebula as determined by *UBV* photometry, near infrared photometry, IRAS far infrared data, and the radio 5 GHz fluxes are in poor agreement. The IRAS and radio estimated luminosities agree very well, and are often somewhat lower than those obtained from *UBV* photometry, with appropriate reddening corrections, and the near IR photometry. This agreement of the radio and IRAS data can be understood if either the errors associated with de-reddening the *UBV* data are large, or if the objects contain pre-main sequence stars. Although there may be slight evidence for the latter explanation for $LkH_\alpha 234$, it is likely with the large reddening corrections ($A_v \sim 5$–10 mag), and in some cases, an uncertain reddening law applied to the *UBV* data, that the IRAS and VLA data give more reliable estimates of the luminosity class of an exciting object for the bipolar nebulae. The IRAS data will provide the best estimate of luminosity and the VLA data can then be used to test whether stellar winds and/or dust are mixed in, or close, to the H II region.

Assuming that we have now been able to estimate spectral classes for the exciting objects, further theoretical work needs to be directed towards an understanding of the physics giving rise to the shape of the bipolar nebulae, the role of magnetic field coupling of B0–B2 stars into the ionised gas, and the relationship of these objects to the larger scale molecular flows seen towards many star formation regions.

Acknowledgements. We thank the VLA for an allocation of observing time, and for assistance at the site, the SERC for financial support of travel, the staff of UKIRT for excellent support in Hawai, Jim Emerson, Peter Phillips, Dave Adams and Andy Lawrence for various useful comments. GG acknowledges receipt of a research studentship from the SERC. We also express our gratitude to Tom Geballe for obtaining the near infrared measurements of BIP 11 at UKIRT and generously allowing us to publish them here, and to Ron Snell, the referee, for a number of helpful suggestions and comments.

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