THE ASTROPHYSICAL JOURNAL, 293:148–153, 1985 June 1

THE *IRAS*[1] GALAXY 0421+040P06: AN ACTIVE SPIRAL (?) GALAXY WITH EXTENDED RADIO LOBES

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Received 1984 August 2; accepted 1984 December 14

ABSTRACT

The infrared bright galaxy 0421+040P06 detected by *IRAS* at 25 and 60 μm has been studied at optical, infrared, and radio wavelengths. It is a luminous galaxy with apparent spiral structure emitting 4×10^{37} W (1×10^{11} $L_\odot$) from far-infrared to optical wavelengths, assuming $H_0 = 75$ km s^{-1} Mpc^{-1}. Optical spectroscopy reveals a Seyfert 2 emission-line spectrum, making 0421+040P06 the first active galaxy selected from an unbiased infrared survey of galaxies. The fact that this galaxy shows a flatter energy distribution with more 25 μm emission than other galaxies in the infrared sample may be related to the presence of an intense active nucleus. The radio observations reveal the presence of a nonthermal source that, at 6 cm, shows a prominent double lobed structure 20–30 kpc in size extending beyond the optical confines of the galaxy. The radio source is 3–10 times larger than structures previously seen in spiral galaxies and may represent a transition between the relatively small, weak sources seen in some active spirals and the stronger, larger ones seen toward elliptical galaxies with active nuclei.

Subject headings: galaxies: Seyfert — galaxies: structure — infrared: sources — radio sources: galaxies

I. INTRODUCTION

The *IRAS* survey is the first unbiased infrared survey with sufficient sensitivity to detect numerous extragalactic objects. The positions and fluxes of over 80 infrared-selected galaxies have been published by Soifer *et al.* (1984), and many ground-based studies are underway to determine their properties. In this paper we present observations of 0421+040P06, which we believe to be of particular interest in that it combines the properties of two hitherto distinct classes of active galaxies: radio galaxies and spirals with active nuclei. The galaxy 0421+040P06 is unusual in being one of only a few galaxies among some 40 of the *IRAS* sample observed to date which has a Seyfert 2 emission-line spectrum and a large double-lobed radio source.

II. OBSERVATIONS AND RESULTS

Soifer *et al.* (1984) reported detections of 0421+040P06 at 25 and 60 μm. Because the galaxy was scanned by *IRAS* on five separate hours-confirming observations (*IRAS Explanatory Supplement* 1985) during the course of the *IRAS* mission, it was possible to co-add all of the scans across the source to obtain measurements at 12 and 100 μm as well. These results are given in Table 1 and reflect the absolute calibration described in the *IRAS Explanatory Supplement* (1985). The statistical uncertainties are less than 15% at 12, 25, and 60 μm and about 20% at 100 μm due to confusion from extended emission from Galactic dust. The uncertainties listed in Table 1 include both statistical uncertainties and those due to the absolute calibration. The values in Table 1 have been corrected for a color-dependent term of order 15% at 12 μm and less than 10% at the longer wavelengths to account for the shape of the energy distribution through the broad *IRAS* passbands (*IRAS Explanatory Supplement* 1985). In deriving these color corrections, an intrinsic spectrum of dust with an emissivity proportional to frequency emitting at 160 K between 12 and 25 μm and at 35 K between 60 and 100 μm has been adopted.

The galaxy was detected on each pass at 60 μm, and over the 218 day interval of the observations there is no evidence for

TABLE 1

SUMMARY OF OBSERVATIONS

A. INFRARED FLUX DENSITIES

Observed Wavelength (μm)	Telescope	Focal Plane Aperture (arcsec)	Observed Flux Density (mJy)[a]
10	IRTF	5 diameter	65 ± 15
12	*IRAS*	45 × 180	120 ± 20
20	IRTF	5 diameter	170 ± 70
25	*IRAS*	45 × 180	310 ± 50
60	*IRAS*	90 × 200	520 ± 90
100	*IRAS*	180 × 240	1200 ± 200

B. RADIO FLUX DENSITIES

Component	Observed Frequency (MHz)	Component Size[b] (arcsec)	Observed Flux Density (mJy)
Total	1490	60 × 60	49 ± 5
	4860	28 × 47	23 ± 2
SE	4860	26 × 18	9 ± 2
NW	4860	28 × 21	10 ± 2

[a] 1 Jy = 10^{-26} W m^{-2} Hz^{-1}.

[b] Fluxes were obtained by integrating the maps within rectangular areas of the quoted dimensions.

[1] The *Infrared Astronomical Satellite* (*IRAS*) was developed and operated by the Netherlands Agency for Aerospace Programs (NIVR), the US National Aeronautics and Space Administration (NASA) and the UK Science and Engineering Research Council (SERC). The Jet Propulsion Laboratory of the California Institute of Technology manages the *IRAS* project for NASA.

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variability greater than the 15% statistical uncertainty in the observations.

Figure 1 (Plate 22) shows an *R* band ($\lambda_0 = 0.64$ μm; $\Delta\lambda$[FWHM] $= 0.1$ μm) picture of the field of 0421+040P06 obtained with the University of Hawaii 2.2 m telescope on 1984 March 23 using the Institute for Astronomy/Galileo 500 × 500 element CCD camera. The most prominent object in the field is a spiral galaxy with an integrated *R* magnitude of 16.3 mag. The observations were calibrated with respect to a set of red photometric standard stars in the cluster M67 (Schild 1984). The main image is approximately 5″ in diameter with a stellar core ($\leq 2''$) of *R* magnitude 18.3 mag. Two spiral arms extend to the north and south by an additional 4″ each. A faint companion lies 11″ northeast of the galaxy and is extended in roughly the direction pointing toward the nucleus of the bright galaxy. A second faint object lies about 5″ to the west of the galaxy.

The identification of the *IRAS* source 0421+040P06 with the bright galaxy was confirmed with measurements at 10 and 20 μm obtained with a bolometer on the NASA IRTF[8] at Mauna Kea, Hawaii. The measurements were obtained with a 5″ diameter focal plane aperture centered on the optical image of the galaxy as determined from the TV guider. As shown in Table 1, there is good agreement between the IRTF and *IRAS* measurements if one extrapolates between the measurements using a 160 K thermal spectrum (as discussed below) to account for the differing central wavelengths of the observations. The region in 0421+040P06 emitting at 12 and 25 μm must be quite small, $\leq 5''$ in diameter, since the ground-based and *IRAS* measurements at 10 and 25 μm are similar despite the large difference in beam sizes.

Spectroscopic observations of the galaxy were made on 1983 December 29, using the Double Spectrograph (Oke and Gunn 1982) mounted on the Hale 5 m telescope of the Palomar Observatory. A long, 2″ wide slit was centered on the brightest point in the galaxy and rotated to include the brighter of the two faint companions, northeast of the main galaxy. A photon counting detector (Schectman 1983) was used between 0.34 μm and 0.54 μm and a Texas Instruments 800 × 800 element CCD between 0.55 and 1.02 μm. The spectral resolution was 300 km s^{-1} at Hβ and 750 km s^{-1} in the red. After field flattening the two-dimensional image, pixels far away from the image of the galaxy were used to measure and subtract the sky background. The data were calibrated with respect to HD 84937 although spillover, refraction, and thin cirrus clouds present during the observations limited spectrophotometric accuracy to roughly 20%. Figure 2 shows the spectrum.

The most notable feature of the spectrum of 0421+040P06 is the presence of exceedingly bright emission lines from the nucleus superposed on a faint continuum. The heliocentric redshift obtained from nine spectral lines in the blue portion of the spectrum is $z = 0.0462 \pm 0.0005$, corresponding to a distance of 185 Mpc for a Hubble constant of 75 km s^{-1} Mpc^{-1}. Some of the emission lines identified in the galaxy are listed in Table 2. The intrinsic widths of the [O III] λ5007 and Hβ lines were determined to be 310 ± 50 km s^{-1} (FWHM) by comparison with Gaussian-smoothed calibration arc lamp lines. The [O III] line shows wings that are considerably broader (1150 km s^{-1} full width at 5% intensity) than the best fit Gaussian smoothed instrumental profile (900 km s^{-1} at 5% intensity). Scattered light within the spectrograph due to the bright nuclear emission lines from the galaxy made it impossible to determine if the emission lines extend into the disk of the galaxy or to obtain a good spectrum of the faint NE companion. The latter is certainly not, however, a strong emission-line source.

[8] The Infrared Telescope Facility (IRTF) is operated by the University of Hawaii under contract with the National Aeronautics and Space Administration.

TABLE 2

OPTICAL EMISSION LINES

Line Identification	Wavelength (μm)	Observed Line Ratio[a]	Dereddened Line Ratio[a]
[Ne V]	0.3346	0.15	0.34
[Ne V]	0.3426	0.37	0.79
[O II]	0.3727	1.76	3.11
[Ne III]	0.3869	0.78	1.28
He I	0.3889	0.12	0.19
[Ne III]	0.3968	0.36	0.56
Hδ	0.4102	0.16	0.24
Hγ	0.4340	0.38	0.49
[O III]	0.4363	0.14	0.17
He II	0.4686	0.19	0.20
Hβ	0.4861	1.00	1.00
[O III]	0.4959	4.42	4.21
[O III]	0.5007	13.70	12.76
[O I]	0.6300	0.72	0.47
[O I]	0.6364	0.26	0.18
Hα + [N II]	0.6563	8.20	4.45
Hα	0.6562	4.50	2.69
[N II]	0.6548	0.81	0.44
[N II]	0.6583	2.45	1.33
[S II]	0.6724	2.40	1.25
[A III]	0.7136	0.30	0.14
[S III]	0.9069	1.03	0.33
[S III]	0.9532	2.66	0.81

[a] Observed line fluxes are ratioed to the flux in Hβ, 2.00×10^{-17} W m^{-2}; dereddened fluxes are ratioed to the flux in the reddening corrected Hβ line, 1.23×10^{-16} W m^{-2}.

In order to obtain the intrinsic line strengths and the shape of optical continuum, it is necessary to estimate the reddening toward the source. The visual extinction, A_v, predicted solely from material within the Galaxy for an object at galactic latitude of $-30°$, is about 0.3 mag. An estimate of the total extinction toward 0421+040P06 can be made from a comparison of the ratios between the hydrogen lines predicted by case B recombination with the observed values. We will show below that the spectrum of the nucleus is that of a Seyfert 2 galaxy; the case B assumption is commonly used in dereddening the line intensity measurements of these objects (Koski 1978; Shuder and Osterbrock 1981). Since the spectral resolution is not high enough to separate clearly the Hα + [N II] blend, a deconvolution of the two lines was attempted using the instrumental profile as given by the arc lines. The ratios of the Hα, Hβ, Hγ, and Hδ line fluxes are internally consistent and imply an extinction of $A_v = 1.7 \pm 0.2$ mag. The difference between the inferred value of 1.7 mag and the 0.3 mag predicted for purely Galactic absorption suggests the existence of significant absorption within 0421+040P06 itself. An A_v of 1.7 mag and a standard reddening curve were used to deredden the line and continuum observations. It should be pointed out that an extensive study of the spectrum of the Seyfert 2 galaxy NGC 1068 (Neugebauer *et al.* 1980) support the assumption of case B recombination and imply a similar amount of internal extinction as that determined for 0421+040P06.

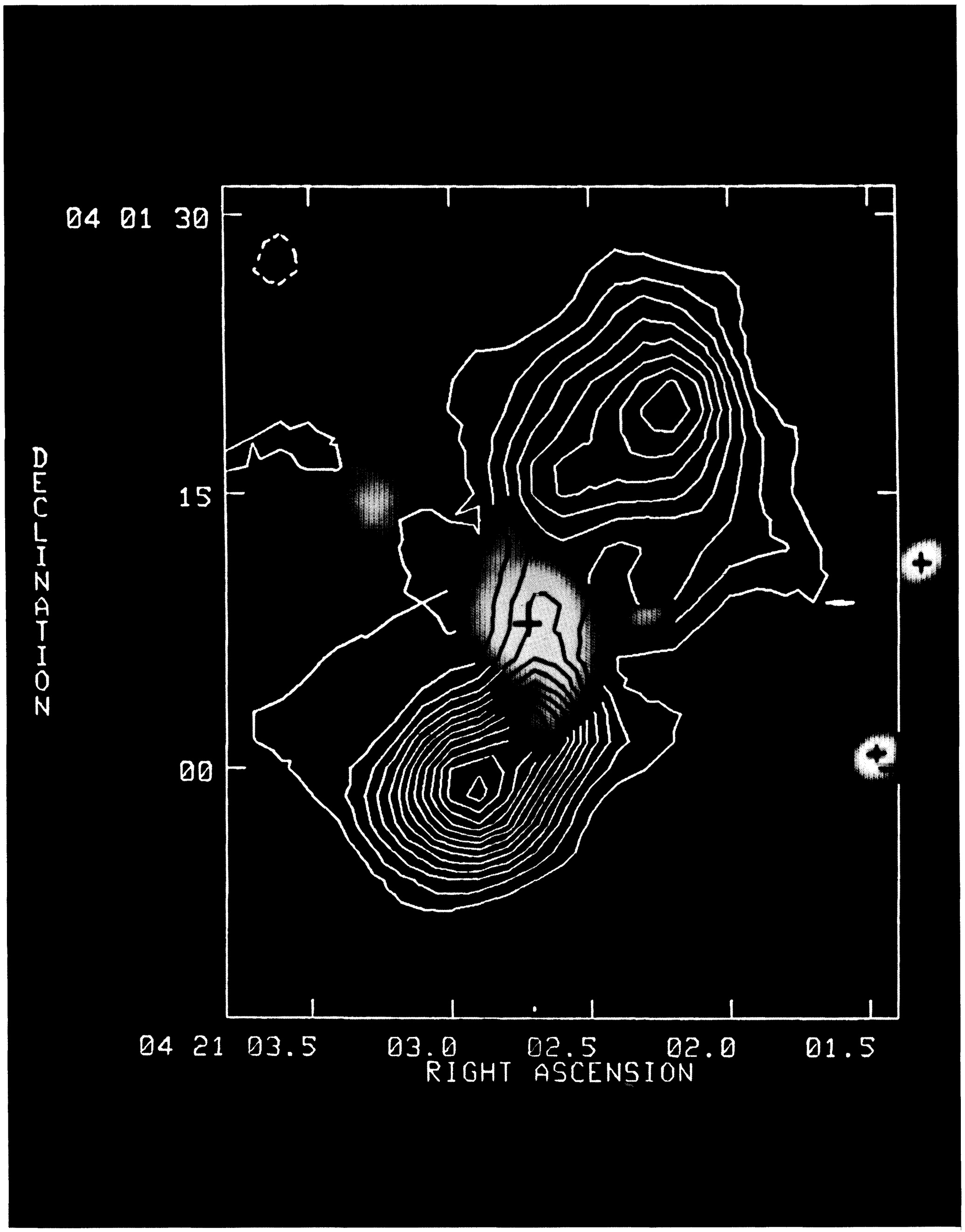

FIG. 1.—An *R* band photograph of the *IRAS* galaxy 0421 + 040P06 is shown with contours of 6 cm emission superposed. The contour levels of the radio map are drawn at −0.2 (*dashed*), 0.2, 0.4, . . . , 3.0 mJy in a 4"2 × 4"0 beam.

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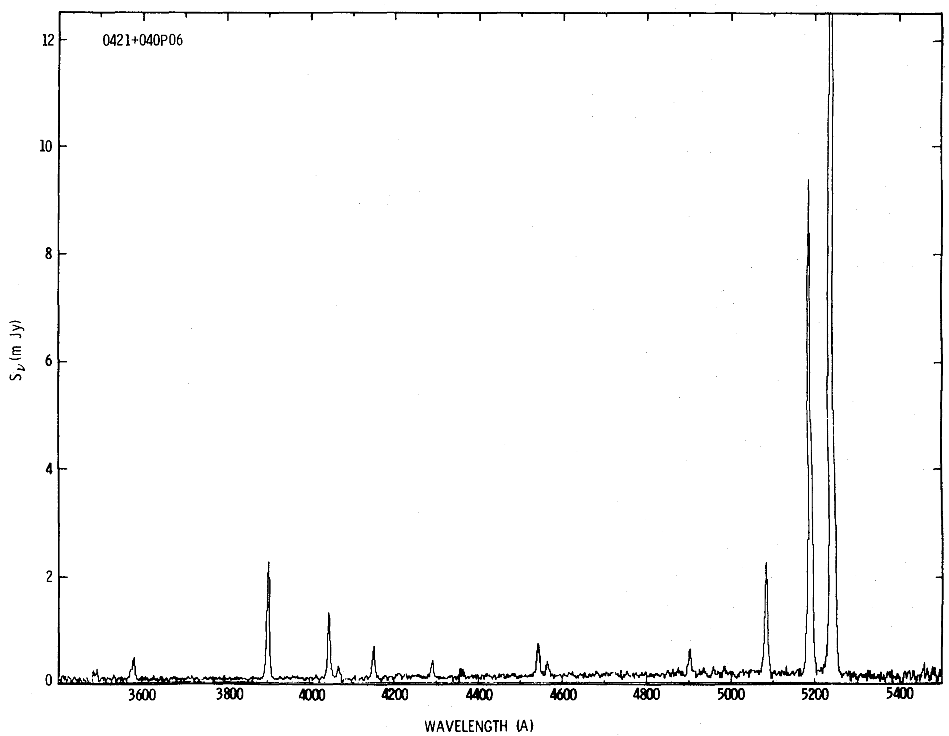

FIG. 2*a*

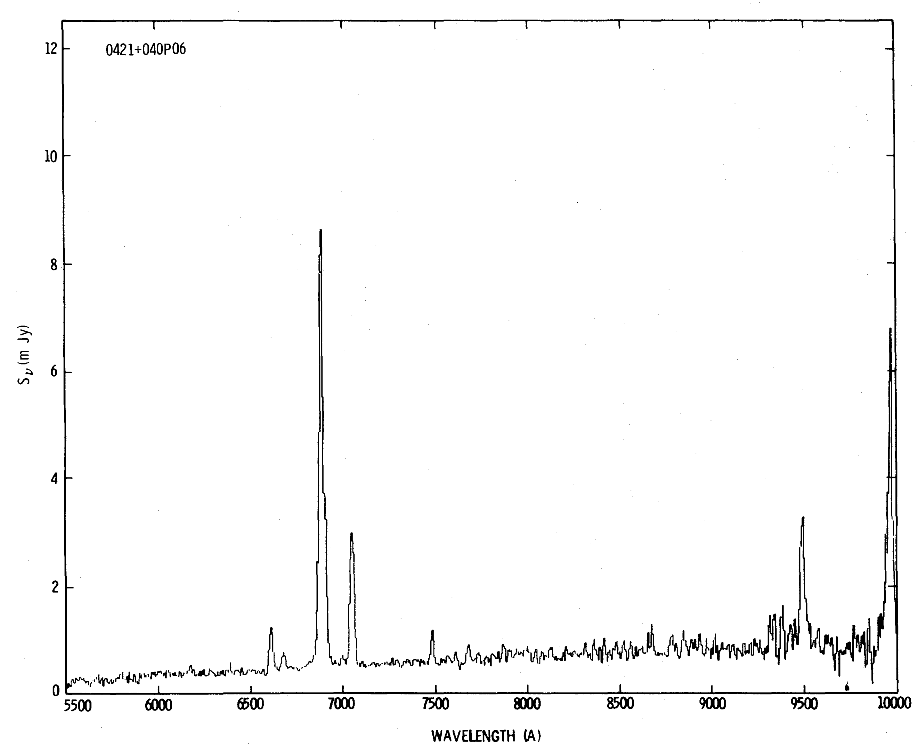

FIG. 2*b*

FIG. 2.—The visual spectrum of 0421 + 040P06. The Hα line has been allowed to go off-scale to bring out lower intensity features of the spectrum. The two panels show the red (*a*) and blue (*b*) portions of the spectrum.

The optical spectrum of the nucleus is characteristic of a plasma ionized by a power-law spectrum in the visible and ultraviolet as may be seen from the reddening corrected line fluxes (Table 2) of the species commonly used to distinguish between objects having different sources of ionization (e.g., Baldwin, Phillips, and Terlevich 1981; Yee 1980). In every aspect, including the ratios of [O III] and He II to Hβ and the presence of [Ne V], the spectrum of the nucleus resembles that of a Seyfert 2 or a narrow-line radio galaxy. 0421+040P06 has unusually narrow lines, but not unprecedentedly so, for such objects (Shuder and Osterbrock 1981). The narrow-line profile with extended wings seen in [O III] is also characteristic of Seyfert and narrow-line radio galaxies (Shuder and Osterbrock 1981). As will be discussed in detail elsewhere (Lonsdale *et al.* 1985), this spectrum is relatively rare in the sample of some 40 other infrared-selected galaxies. Most of these other galaxies show emission lines only from low-excitation species.

The observed visual continuum emission is too faint to allow identification of any stellar absorption features. It can be fitted by a power law of index $\alpha = -3$ (defined as $S_\nu \propto \nu^\alpha$) normalized to 0.25 mJy at 0.55 μm. The unreddened visual continuum is roughly fitted by a power law with $\alpha \approx -1$ normalized to 1.38 mJy at 0.55 μm. If all the observed continuum is the power-law ionizing continuum, then the ratio of Hβ to the continuum places 0421+040P06 in the middle of Yee's (1980) diagram of Hβ versus L_{NT} (luminosity in the nonthermal continuum), consistent with its classification as a Seyfert 2. Even if as much as 50% of the continuum arose from starlight—which cannot be ruled out on the basis of these data—the Hβ-L_{NT} ratio would still be consistent with a Seyfert 2 classification.

Radio observations of 0421+040P06 were made at wavelengths of 6 and 20 cm using the Very Large Array of the National Radio Astronomy Observatory.[9] The 6 cm observations were made with the B configuration on 1984 February 4 and in the C configuration on 1984 May 7. Observations at 20 cm were made using the C configuration on 1984 May 6. The maps were calibrated and cleaned following standard procedures and were referenced to 3C 48. The 6 cm map obtained in the C configuration has a synthesized beam size of 4".2 × 4".0 at a position angle of $-29°$ and is shown in Figure 1 superposed on the optical image. The radio and optical images have been registered with an accuracy of $\pm 1''$.

The radio map shows an extended, double-lobed radio source straddling the position of the optical galaxy. The two radio lobes seen at 6 cm appear to be located at the ends of the spiral arms, just outside the visual boundary of the galaxy. The separation between the lobes is 23" (21 kpc), and the total extent of the radio source measured to the lowest significant contour is 41" (37 kpc). Both 6 cm lobes are themselves extended with sizes of about 12", corresponding to a linear dimension of 11 kpc. At 20 cm the spatial resolution is inadequate to distinguish between the two lobes but the map is consistent with two sources of roughly equal intensity at the locations of the two 6 cm lobes. The 20 cm–6 cm spectral index for the total emission from the galaxy is -0.6 ± 0.1 and the integrated 20 cm radio power is 2.4×10^{23} W Hz^{-1}. Except for a bridge of emission connecting the main lobes, no radio emission brighter than 0.8 mJy is detected from a nuclear point source, nor is 6 cm emission brighter than 0.8 mJy detected from either of the faint optical companions.

The energy distribution between radio and optical wavelengths is shown in Figure 3. The galaxy emits 3×10^{37} W between 10 and 100 μm. Adding in the contributions from the observed nuclear optical continuum, a power-law interpolation between 1 μm and 10 μm an an extension of the far-infrared spectrum to infinite wavelength assuming a 35 K temperature and grains with an emissivity proportional to frequency leads to an estimate of 4×10^{37} W for the bolometric luminosity of this object. This value ignores the contribution of

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

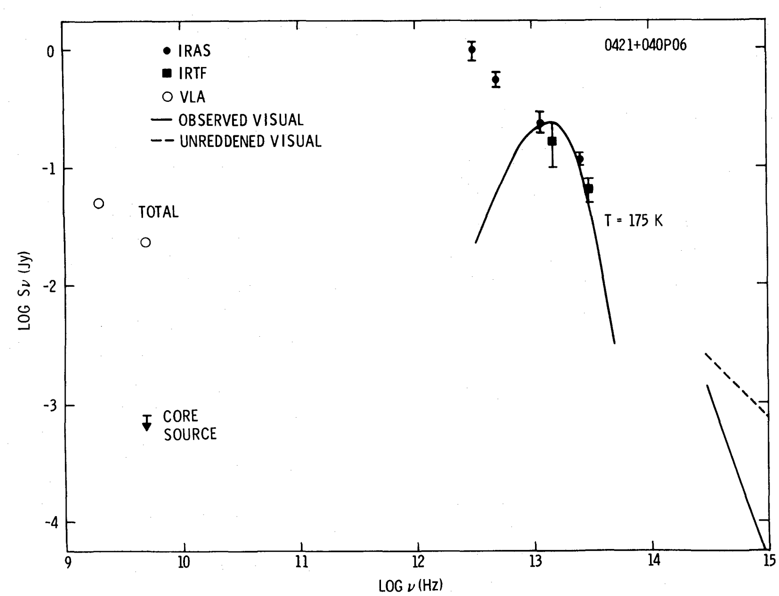

FIG. 3.—The spectral energy distribution of 0421+040P06 from radio to visual wavelengths. An upper limit is shown for the 6 cm brightness of a nuclear point source in a 4".2 × 4".0 beam. The visual spectrophotometry is represented by a power law fitted to the continuum and refers only to the nuclear source. The energy distribution of thermal emission by grains with an emissivity proportional to frequency at a temperature of 175 K is shown.

TABLE 3

DERIVED PROPERTIES[a]

Property	Value
Distance	185 Mpc
10–100 μm luminosity	2.8×10^{37} W
Unreddened visual luminosity (0.3–0.95 μm)	0.3×10^{37} W
Total luminosity	4.3×10^{37} W
Optical spectral index (dereddened)	-1.0 ± 0.1
Hβ luminosity	4.9×10^{34} W
[O III] luminosity	8.4×10^{35} W
[O II] luminosity	1.5×10^{35} W
Radio luminosity (10 MHz–100 GHz)	3.4×10^{33} W
Radio spectral index	-0.6 ± 0.1
P(1415 MHz)	2.4×10^{23} W Hz^{-1}

[a] $H_0 = 75$ km s^{-1} Mpc^{-1}.

the disk of the galaxy at visual wavelengths, but the correction is not likely to exceed 10% of the total.

III. DISCUSSION

Morphologically, 0421+040P06 appears to be an undistorted two-armed spiral galaxy. The absolute visual magnitude can be estimated to be -20.6 mag, typical of spirals, using the integrated $R = 16.3$ mag, corrected for reddening and assuming typical spiral galaxy colors ($V-R = 0.5$ mag). Spectroscopically, 0421+040P06 shows intense, narrow emission lines suggesting a power-law ionization spectrum.

The galaxy 0421+040P06 emits the bulk of its energy in the far-infrared and is the first active galaxy to be selected on the basis of its far-infrared emission. Soifer *et al.* (1984) characterized galaxies by the ratio of their far-infrared (80 μm) to blue luminosities, $L(80)/L(B)$. The integrated, apparent blue magnitude is estimated to be 16.8 mag from the spectrophotometry and the 2 mag difference between the brightness of the nuclear region and the entire galaxy in the R image. The resultant $L(80)/L(B)$ ratio is 6.5 which places 0421+040P06 in the middle of the range of infrared-selected galaxies but among the most extreme 5% of all spiral galaxies (de Jong *et al.* 1984; Soifer *et al.* 1984). The galaxy 0421+040P06 differs from most of the other galaxies in the infrared sample in having detectable 25 μm emission; most of the other galaxies in the *IRAS* sample were detected only at 60 and/or 100 μm. The fact that this galaxy is also one of the few objects to contain an active nucleus suggests that the presence of hot (> 160 K) material, as evidenced by substantial 25 μm emission, may provide a method for finding galaxies with active nuclei purely by their *IRAS* characteristics. In this context it is interesting to note that the radio galaxy 3C 390.3 shows a similar component, also, apparently, due to heated dust (Miley *et al.* 1984).

The existence of a sharp break in the energy distribution between 10 μm and the visual argues against a single power-law spectrum extending over the entire spectral region. Rather, the data suggest a nonthermal power-law spectrum in the optical/ultraviolet and reradiation in the far-infrared of absorbed short-wavelength energy. The presence of significant amounts of absorbing dust is suggested by the high visual extinction required to account for the optical line ratios.

The emitting material in 0421+040P06 must exhibit a broad range of temperatures to account for the relatively flat 10–100 μm energy distribution. From the strength of the emission observed in the various *IRAS* bands, it can be shown that for blackbody grains 40–200 K material is required, while for grains with an emissivity proportional to frequency 35–160 K material is required. The optical-infrared energy distribution of 0421+040P06 is similar to that of the Seyfert galaxy NGC 4151. The latter object has been modeled by Rieke and Lebofsky (1981) in terms of a two-component model—an optical-ultraviolet power-law continuum that is partially absorbed by grains that reradiate the energy in the infrared. A characteristic of the model is a significantly flatter energy distribution, i.e., more 10 and 25 μm emission, than is found in starburst galaxies such as M82 (Telesco and Harper 1980). Higher spatial resolution measurements in the infrared will be required to determine whether the infrared originates in a disk and is thus attributable to a starburst (cf. the discussion of Telesco, Becklin, and Wynn-Williams 1984 for NGC 1068) or whether the infrared comes from a small region heated solely by the active nucleus.

One of the most unusual features of 0421+040P06 is the combination of apparent spiral structure and the large extent of its radio emission. Narrow-line radio galaxies have emission-line spectra similar to Seyfert 2 galaxies as well as large (~100 kpc), powerful radio sources (Ekers *et al.* 1981). They are, however, elliptical galaxies with radio powers large compared with 0421+040P06. Ulvestad and Wilson (1984) found that weak double or triple linear radio sources are common in Seyfert spirals, but with characteristic sizes smaller than 2 kpc and with the radio sources found within the optical confines of the galaxy (Wilson 1982). The largest radio structures previously seen in Seyferts are in Markarian 34, 78, and 315 (Ulvestad and Wilson 1984) and NGC 5548 (Ulvestad, Wilson, and Wentzel 1982). The radio sources in these galaxies have diameters in the range 2.5–8.6 kpc (adjusted to $H_0 = 75$ km s^{-1} Mpc^{-1}), a factor of 4–10 smaller than the double-lobed structure seen toward 0421+040P06. Assuming that the curved extensions to the north and south of the visible galaxy are true stellar spiral arms and not peculiar gas jets or tidal tails, 0421+040P06 is as unusual as a radio galaxy as it is as a Seyfert galaxy.

The double-lobed structure, the nonthermal spectrum and the fact that the radio emission originates outside of the visible extent of the galaxy together rule out thermal emission from H II regions or nonthermal emission from supernovae in the disk of the galaxy as mechanisms for producing the observed radio emission. The double-lobed structure is most naturally explained in terms of ejection of energetic material in diametrically opposed jets from the active nuclear source. Wilson (1982) accounts for many of the features of Seyfert radio sources by the beaming of material in the plane of the galaxy. The disruption of the jet by the interstellar medium is thought to be responsible for the small sizes of the typical Seyfert galaxy radio sources. In classical radio galaxies, on the other hand, the jets escape to large distances beyond the optical confines of the galaxy, both because they are intrinsically more powerful and because there is little intervening interstellar material in the giant elliptical galaxy hosts. There are some examples of possible transition cases: kiloparsec-scale radio emission related to the optical emission-line gas is seen in 3C 305 (Heckman *et al.* 1981), 3C 293 (van Breugel *et al.* 1984) and 4C 26.42 (van Breugel, Heckman, and Miley 1984) and may indicate the interaction of the jets of these powerful radio galaxies with the interstellar medium (e.g., Miley 1983) and the inhibition of the free expansion of the jets.

The galaxy 0421+040P06 may represent another transition case, although it is of considerably lower power than the above-mentioned radio galaxies. Modifications of Wilson's (1982) model for the radio emission from Seyferts, such as inclining the beaming axis slightly to the disk of the galaxy, may account for the large size of the structures seen in 0421+040P06. A striking feature of 0421+040P06 is the fact that the radio jets appear to bend in an "S" shape that is aligned with the spiral pattern in the optical image. We note that the "spiral arms" visible in the *R* image could arise from Hα emission and not from starlight. The emission lines could originate in gas excited by the passage of the jets and could outline the dense material responsible for bending the radio jets (cf. the discussion of 3C 293 by van Breugel *et al.* 1984). A more detailed discussion of this apparent link between the radio and optical emission must await a higher quality optical image and additional optical spectroscopy. Radio polarization data should also be of interest since optical line/radio continuum associations are found to have low radio polarization (e.g., Miley 1983).

The fact that the NE companion is extended in the direction of the line connecting it to the nucleus of 0421+040P06 is suggestive of an interaction between the two objects. The nature and importance of the optical companions of 0421+040P06 will not be known until additional optical spectroscopy is obtained. It is important to recall that extreme infrared activity appears to be closely related to encounters between nearby galaxies (Lonsdale, Persson, and Matthews 1984) and that the companions might play an important role in 0421+040P06 as well.

Most known active galaxies have been found through surveys at radio (radio galaxies and radio-loud quasars), ultraviolet, or X-ray wavelengths (Seyferts and radio-quiet quasars). 0421+040P06 is the first active galaxy selected solely by its far-infrared emission; it has properties intermediate between previously known classes of active galaxies. It remains to be seen whether 0421+040P06 is unique or whether it represents the first object to be found that bridges an apparent gap between Seyfert galaxies and narrow-line radio galaxies. There may exist a whole continuum of objects with varying radio sizes and powers that are too weak in either the radio, ultraviolet, or X-rays to have been identified in previous searches, but which can be identified by their infrared emission.

We would like to thank Drs. R. Ekers, M. Goss, and G. Lake for useful discussions and Carol Oken for assistance in coadding the *IRAS* data. We would like to thank N. Devereux, G. Hill, and D. dePoy for assistance with the ground-based observations. One of us (C. A. B.) would like to thank Dr. John Bahcall for his hospitality at the Institute for Advanced Study where a draft of this manuscript was prepared. This work was supported in part by NSF grants AST 82-17118 and AST 82-11591.

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