

A 2.2- $\mu\text{m}$  SEARCH FOR VARIABLE GALACTIC PLANE RADIO SOURCES

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## ABSTRACT

A search for infrared counterparts of some of the variable galactic plane radio sources identified by Gregory and Taylor has yielded two detections. Of these, one is of the star LSI + 61°303, already identified by Gregory *et al.* as the counterpart of GT 0236 + 610, while the other, GT 2100 + 468, appears to be a heavily obscured object which may be either galactic or extragalactic.

## I. INTRODUCTION

Gregory and Taylor (1981, 1983) have surveyed much of the galactic plane for variable radio sources which might be similar to the well-known peculiar object SS433. Subsequent VLA observations (Gregory and Taylor 1981; Taylor *et al.* 1984) have refined the positions of a number of these objects, many of which were shown to be compact or unresolved. Of the objects with accurate positions, however, only one—GT 0236 + 610—could be identified with a visible star, LSI + 61°303 (Gregory *et al.* 1979). The remaining objects showed no convincing coincidences with visible stars on the Palomar Sky Survey prints (Taylor *et al.* 1984). The absence of a visible candidate object at the position of any of the other sources is taken to indicate that they are heavily obscured or subluminal galactic sources, or that they are extragalactic. The concentration toward the galactic plane of these sources suggests that some at least are galactic. On the other hand, H I absorption measurements of three of the sources (Taylor and Seaquist 1984) indicate that these three are all at distances of over 12 kpc, and hence are likely to be extragalactic.

In an effort to detect heavily obscured sources, such as a more distant SS433 or objects such as Cyg X-3, we have made 2.2- $\mu\text{m}$  observations at the positions of 11 of the GT variables with accurate positions. None other than GT 0236 + 610 and GT 2100 + 468 was convincingly detected; the upper limits (set by confusion) at the positions of the other sources imply either low luminosities or very large distances.

## II. OBSERVATIONS AND RESULTS

The sources that were observed were selected from the lists of Gregory and Taylor (1981) and Taylor, Seaquist, and Gregory (1984). Only sources that were compact or unresolved were included in the observing program. The final list totaled twelve sources, of which one, GT 1943 + 228, was not observed because of its unfavorable right ascension. The remaining eleven sources are listed in Table I.

All of the observations were made using the Palomar 5-m Hale Telescope and the f/70 chopping secondary. An InSb photovoltaic detector was used. The initial search was made using a 10"-diam beam and a standard 2.2- $\mu\text{m}$  ( $K$ ) filter\*. The chopper throw was 15" in declination. The telescope was positioned by offsetting from nearby AGK<sub>3</sub> stars. Tests

\*Filter properties and standard star magnitudes for the  $J$ ,  $H$ , and  $K$  filters are given in Elias *et al.* (1982). The remaining filters used are  $L$  ( $\lambda_c = 3.69 \mu\text{m}$ ,  $\Delta\lambda = 0.64 \mu\text{m}$ ),  $M$  ( $\lambda_c = 4.79 \mu\text{m}$ ;  $\Delta\lambda = 0.61 \mu\text{m}$ ) and  $N$  ( $\lambda_c = 10.6 \mu\text{m}$ ;  $\Delta\lambda = 5.1 \mu\text{m}$ ).

done offsetting from one reference star to another showed that the setting errors were typically less than 2". The nominal positions of the sources were thus well within the 10" beam. At every position, a measurement was made; deliberately, no attempt was made to center up or maximize the signal. The resulting fluxes are given in Table I. The measured fluxes, with the exception of GT 0236 + 610, show a scatter about zero flux of roughly a millijansky. This scatter is undoubtedly due to confusion from faint sources in the galactic plane, since the uncertainty in individual measurements is considerably less.

GT 0236 + 610 showed a substantial signal, as expected from its prior identification with a reddened B star. GT 2100 + 468 also showed a statistically very significant signal, though it is possibly unrelated to the radio source (see below, Sec. VI). Additional photometry was done on these two sources, which is summarized in Table II. This photometry is discussed in Sec. IV.

## III. FLUX LIMITS

Of the ten positions that were measured besides GT 0236 + 610, three show negative fluxes of more than  $2\sigma$ , and three show positive fluxes of more than  $2\sigma$ . The remaining four positions show fluxes that are not significantly different from zero. This result suggests that the measurements are the result of confusion: chance occurrences of stars of  $K \sim 15$  mag in the signal or one of the reference beams. The dispersion in the measurements, 1.2 mJy, is therefore a better measure of their accuracy than the formal statistical uncertainties, which are typically 0.2 mJy or less. The upper limit on the flux from any given position is thus about 4 mJy. The average flux from all ten positions other than GT 0236 + 610 is  $-0.3$  mJy, with an uncertainty (derived from

TABLE I. 2.2- $\mu\text{m}$  measurements.

GT <sup>a</sup>	$f_v(2.2 \mu\text{m})(\text{mJy})$
2100 + 468 <sup>b</sup>	$+1.6 \pm 0.1$
2134 + 539	$-0.2 \pm 0.1$
2156 + 531	$+0.5 \pm 0.1$
2157 + 566	$-0.0 \pm 0.2$
2203 + 559	$+0.2 \pm 0.1$
0026 + 627	$-0.3 \pm 0.1$
0106 + 613	$-3.0 \pm 0.3$
0236 + 610 <sup>b</sup>	$467 \pm 21$
0252 + 574	$+0.0 \pm 0.1$
0459 + 415	$+0.1 \pm 0.1$
0554 + 242	$+0.3 \pm 0.3$

<sup>a</sup>Identification from Gregory and Taylor (1981); Taylor, Seaquist, and Gregory (1984).

<sup>b</sup>Additional photometry in Table II.

TABLE II. Infrared photometry of GT 2100 + 468 and GT 0236 + 610.

Source name	Date (UT)	Observed magnitudes <sup>a</sup>						Beam diam. (arcsec)
		<i>J</i>	<i>H</i>	<i>K</i>	[3.7]	[4.8]	[10]	
GT 2100 + 468	8 Oct 84	17.62(16)	15.81(11)	14.05(6)	—	—	—	10
	6 Nov 84	17.10(13)	15.69(10)	14.26(8)	12.52(15)	—	9.78(110) <sup>b</sup>	5
GT 0236 + 610 <sup>c</sup>	9 Oct 84	8.56(7)	8.19(7)	7.83(5)	7.43(8)	7.15(21)	6.60(15)	10
	4 Nov 84	8.59(4)	8.22(3)	7.86(3)	7.43(6)	7.29(18)	6.86(23)	10

<sup>a</sup> Percent errors are given in parentheses following the individual measurements.

<sup>b</sup> Nondetection:  $3\sigma$  upper limit is [10] > 8.2 mag.

<sup>c</sup> Magnitudes corrected by 3% or less for contamination of reference beam by star 11" to the south.

the dispersion) of 0.4 mJy. Since this result is close to zero, it is clear that the mean 2.2- $\mu$ m flux from the unidentified radio sources must be small, less than about 0.9 mJy ( $3\sigma$  limit, corresponding to  $K = 14.6$  mag).

Based on the flux data alone, there is thus no evidence for an infrared identification of any of the ten previously unidentified radio sources. However, measurement of the source at the position of GT 2100 + 468 showed it to have unusual colors, not typical of a reddened star (as discussed below). For the remaining sources, convincing identifications might be made in the infrared using higher spatial resolution. Observations at roughly 1" resolution should reduce the confusion level by a factor of 10.

#### IV. LSI + 61°303

This object was readily detected at 2.2  $\mu$ m at a level several hundred times higher than that of the other objects in Table I. It has already been studied in some detail at other wavelengths (Gregory *et al.* 1979; Bignami *et al.* 1981); Maraschi, Tanzi, and Treves 1981; Hutchings and Crampton 1981; Taylor and Gregory 1982) so it will be discussed rather briefly here.

The radio data show a definite periodic behavior of irregular amplitude and period  $26.52 \pm 0.04$  days (Taylor and Gregory 1982); the radial velocities measured from visual spectra are consistent with this period, and imply that the object is a close binary, where the primary is a rapidly rotating, main-sequence, early B star, and the secondary is of relatively low mass, 1–2  $M_{\odot}$  (Hutchings and Crampton 1981). The visible and ultraviolet data indicate that the visual extinction to the object is roughly  $A_V = 3.3$  mag (Gregory *et al.* 1979; Maraschi, Tanzi, and Treves 1981). The binary is also a definite x-ray source and possible  $\gamma$ -ray source (Bignami *et al.* 1981).

Models for LSI + 61°303 involving a B-star primary and neutron-star secondary have been discussed by Maraschi and Treves (1981) and Taylor and Gregory (1982). Infrared emission from the binary has not been explicitly discussed, but it is clear that there should be emission from a shell or accretion disk in the system, as well as from the B star itself.

Out to about 2.2  $\mu$ m, the fluxes are what would be expected from a B star reddened by  $A_V \sim 3.3$  mag (Gregory *et al.* 1979), but beyond this wavelength there is evidence for excess emission, which is probably the dominant source of flux at wavelengths beyond 5  $\mu$ m. Both sets of infrared data were obtained near the presumed time of radio maximum, based on the period of Taylor and Gregory (1982). The excess emission, which amounts to  $\sim 50$  mJy at 10  $\mu$ m, should be compared with the maximum flux in the radio of  $\sim 150$  mJy

(Taylor and Gregory 1982). It thus appears that the 10- $\mu$ m excess is due to optically thin free-free or synchrotron emission. Certainly, simple models involving an optically thick stellar wind or accretion disk do not fit the data well.

The two sets of infrared measurements, taken about a month apart, show no evidence of variability. The most accurate photometry is at the wavelengths where the stellar contribution dominates, so limits on variability are roughly 10% for the star and 50% for the flux-excess component. The interval between the infrared measurements was 26 days, almost the same as the 26.52-day binary period, so the apparent lack of variability may be deceptive.

#### V. GT 2100 + 468

*J, H, K, L'* (3.7  $\mu$ m) and 10- $\mu$ m data for this object are given in Table II. The November 1984 measurements were made using a smaller (5") beam and centering up on the position of peak 2.2- $\mu$ m flux. This was found to be the same as the radio position, to within our uncertainties of  $< 2''$ . This positional coincidence supports the identification of the infrared source with the radio source, although it is not compelling.

A stronger argument can be made using the infrared colors. These are not those of a normal, reddened star [see Hyland (1981) for a discussion of this argument], as  $J - H$  and  $H - K$  are roughly equal, at 1.4 mag, whereas for a reddened K or M giant  $H - K$  of 1.4 mag would imply  $J - H$  near 2.5 mag.  $K - L'$  is roughly 1.7 mag, whereas a value of 1.3 mag or less would be expected from a reddened M star for the observed  $H - K$  color. The brightness of the source at  $L'$  is in fact sufficient to make it unlikely to be due to chance coincidence.

Colors such as those observed could be produced by an additional flux component, such as heated dust. It is possible to produce these colors with two normal stars, one much more reddened than the other. A detection at 10  $\mu$ m would exclude this possibility definitely.

If the infrared source is the same as the radio object, one can ask whether this helps define the nature of the object. Taylor and Seaquist (1984) have measured H I absorption for the radio source, and have found it to be beyond all the H I in the galactic disk. This places it at a distance of at least 12 kpc, and thus suggests that it is extragalactic. It must in any case be fairly heavily reddened.

The infrared colors of GT 2100 + 468 resemble those of Cyg X-3, although GT 2100 + 468 is about ten times fainter. Since Cyg X-3 is at a distance of roughly 12 kpc (Dickey 1983), GT 2100 + 468 could be an object of similar type with a somewhat greater distance and smaller luminosity. There

is, however, no catalogued x-ray source at the position of GT 2100 + 468.

If GT 2100 + 468 is extragalactic, it is quite possibly similar to BL Lac. Its infrared colors are like those of BL Lac reddened by roughly 5 mag of visual absorption. GT 2100 + 468 is roughly ten times fainter than BL Lac when BL Lac is faint in the infrared.

The infrared observations of GT 2100 + 468 are thus not sufficient to distinguish between a galactic and extragalactic object. More systematic observation in the infrared might reveal variability whose characteristics could be more informative. Further observations should be made to improve the accuracy of the infrared position to better than 1", which would presumably strengthen the identification with the radio source. It would also be useful to set more definite limits on the x-ray emission from the object.

## VI. CONCLUSIONS

A search in the infrared for ten previously unidentified compact, variable radio sources has yielded one possible identification. The remaining nine objects must have an average flux density less than about 0.9 mJy at 2.2  $\mu$ m.

The one possible identification, with GT 2100 + 468, is convincing but does not help in determining whether the source is galactic or extragalactic in nature.

Infrared observations of LSI + 61°303, previously identified with GT 0236 + 610, show it to have the colors of a reddened B star out to 2.2  $\mu$ m. At longer wavelengths, there is an excess which dominates the total flux at wavelengths longer than 5  $\mu$ m.

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