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DETECTION OF NEW CELESTIAL OBJECTS AT FAR-INFRARED WAVELENGTHS

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ABSTRACT

During a high-altitude balloon flight, sources of far-infrared radiation have been detected with apparent fluxes $\gtrsim 3 \times 10^{-12}$ W cm^{-2} in the spectral band 50–500 μ. While the sources are not uniquely identifiable with any well-known class of celestial objects, two associations should be noted. Many of the objects lie close to local stars; there is also a tendency to cluster around the ecliptic plane. Alternatively, a new class of celestial objects may have been observed.

Subject headings: infrared sources

I. INTRODUCTION

Apart from the pioneering work of Hoffman *et al.* (1967), who conducted a partial sky survey with a 1-inch telescope, in the 300–360-μ wavelength range, and another partial survey by Friedlander and Joseph (1970) in the 100-μ region, there has been no survey that has systematically covered a large fraction of the sky in the far-infrared. In order to perform such a survey, we developed a balloon-borne telescope with two far-infrared detectors. During the first flight of this system, a number of bright sources, including the Moon, were repeatedly detected.

II. INSTRUMENTATION

The observations were made with a 40-cm f/2.5 Newtonian telescope. Chopping was accomplished by rocking the secondary mirror at about 8 Hz, to produce a beam throw of 0°.7 in cross-elevation. Condensing optics consisted of two brass light-pipes mounted one above the other inside the liquid-helium dewar. Each light-pipe was terminated by its own integrating sphere enclosing a silicon bolometer of dimensions $5 \times 5 \times 0.4$ mm. Diaphragms in the entrance apertures of the light-pipes, in the focal plane of the telescope, defined a field of view for each detector of 1° in elevation and 0°.65 in cross-elevation. The fields of view of the two detectors were nearly adjacent, with centers separated in elevation by 1°.

Long-wave pass filtering was achieved by using 2 mm of crystal quartz for the dewar vacuum window; 1.8 mm of Teflon at 100° K on the radiation shield; and 2 mm of crystal quartz with 0.15 mm of black polyethylene at 1.8° K at the light-pipes. The spectral response of the detector-filter combination was measured relative to that of a Golay cell with a diamond window, and was found to cut on sharply at 50 μ and remain fairly flat from 60–500 μ. The overall transmission of the filters is estimated to be 10 percent at 100 μ and 20 percent beyond 200 μ. In laboratory testing with these filters, the two detectors were found to have noise equivalent power (NEP) at 8 Hz of about 2 and 4×10^{-12} W Hz$^{-1/2}$, when exposed to a 225° K background.

For flight, the telescope was locked in elevation and driven continuously in azimuth with an average period of rotation of 4 minutes. One has a strong measure of confidence that a "genuine" celestial object has been seen when detected repeatedly at the same celestial coordinates through this mode of scanning. The method used for the continuous monitoring of telescope orientation has been described by Joseph (1974).

For this flight, the elevation angle of the telescope was set at 26°.5, in order to sweep through the galactic center region, but a last-minute delay in the balloon launch finally prevented this observation. The balloon was launched at 1857 CDT on 1973 September 20 from the NCAR Scientific Balloon Facility in Palestine, Texas, and floated at an altitude of 30 km for about 10 hours.

III. RESULTS

In the post flight data analysis, the telemetered signals from the detector preamplifiers were fed into a lock-in amplifier together with a telemetered synchronous reference signal, derived from the rocking secondary. The resulting signal from each detector was recorded on a strip chart which was then examined for possible sources. To be accepted, a "possible source" had to project beyond the normal peak-to-peak noise fluctuations, i.e., exceed the rms noise about six times. To avoid any possible bias, the primary scanning of the record was carried out before the reduction of the telescope orientation data. Only after the "possible sources" had been noted were the orientation data reduced and the celestial coordinates computed for each. Further, a genuine signal was required to meet additional criteria beyond amplitude exceeding the noise: both the shape and initial polarity of the signal had to be consistent with that expected from a point source scanned in the known direction of rotation of the telescope. Noise spikes can be large, but differ significantly in shape from expected signals.

During the flight, about half the sky was scanned and a total of 82 "possible sources" were found. For each, the corresponding celestial coordinates were calculated. Four of these "possible sources" are sightings of the

Moon. The sequence of lunar detections follows the pattern expected for observation of an extremely bright object in the east whose angular size is comparable to the field of view. At $04^h24^m24^s$ CDT the signal in the lower detector saturated; at $04^h28^m24^s$ both detectors saturated; at $04^h32^m32^s$ the upper detector alone was saturated. The calibration of our orientation measurements was based on these sightings and the known position of the Moon. Due to the finite size and extreme brightness of the Moon the accuracy with which we know where the telescope was pointing is $\pm 0\overset{\circ}{.}5$. Repeated sightings of a point source could yield apparent positions separated by up to 2°, corresponding to the object having been detected at the extremities of the field of view. Using this criterion, "possible sources" were then matched against each other, and 12 objects were identified as having been detected two or more times at the same celestial coordinates.

Those "possible sources" that were detected more than once (i.e., $\leq 2°$ separation) we have termed "probable sources," and classified into two groups: class A, repeated detection of a source on two or more azimuthal scans; class B, simultaneous detection of a source in both detectors, but no repeated detection on later scans. All objects in these categories are listed in table 1, with the exception of the sightings of the Moon.

If the 82 "possible sources" were randomly distributed, then we would expect to find only one pair within 2°. The probability for observing eight repetitions (the class A events) is less than 10^{-5}. For comparison, about 80 of the largest noise spikes were selected on the flight record; these had shapes that differed from that expected for genuine point sources. For each noise spike, the celestial coordinates were computed from the known telescope orientation. Only one pair was found within a 2° separation. We conclude that the class A "possible sources" are not randomly distributed (as are genuine noise spikes), but their repeated sightings do have astronomical significance. For the class B sources, we note that the lunar sightings could saturate one detector while leaving the other with no detectable signal; the two channels were obviously very effectively isolated against crosstalk.

While the remainder of the discussion will be confined to the 12 objects listed in table 1, we wish to note in passing that it is entirely possible that a number of the remaining "possible sources" were not detected a second time only because the scanning pattern of our telescope on the sky was not always closed. This was due in part to variations in the azimuthal scan period, partly to a slightly smaller half-power beamwidth for the telescope than the nominal 1° defined by the diaphragm apertures, and partly to a small irregular motion ($\sim 0\overset{\circ}{.}5$) of the telescope in elevation angle throughout the flight.

Unfortunately, the in-flight noise level was several times larger than it had been in laboratory testing. The fact that we did not detect Jupiter means that our minimum detectable apparent flux for this flight was about 3×10^{-12} W cm^{-2}. The apparent fluxes of the "probable sources" listed in table 1 are based on this figure.

IV. DISCUSSION

The repeated detections, in most cases 4 or more minutes apart (two sources detected in the southeast early in the flight were detected again in the southwest late in the flight), for the 12 "probable sources" listed in table 1, together with the conformity of signal shape and initial polarity to that expected for the chopping and scanning of the telescope beam, argue strongly that these sources represent the detection of celestial objects with large apparent fluxes in the far-infrared. With the reduced sensitivity that appeared on this initial flight of the instrument we would not have expected to detect any of the far-infrared sources that have previously been reported, with the exception of the intense galactic center source (Hoffmann and Frederick 1969), and our chance to observe this region was precluded by the unfortunate delay in the balloon launch.

Before examining the possible interpretation of these results, we wish to consider whether our probable sources should or could have been detected by previous surveys in nearby spectral regions. The only previous survey in the far-infrared with continuous sky coverage was that carried out by Hoffmann *et al.* (1967), who detected only the Moon. Although their observations were made mostly over the opposite half of the northern sky, there is some overlap in the celestial areas covered by the two flights, and their minimum detectable sensitivity was similar to ours. However, their observations were carried out in the longer wavelength and relatively narrower 300–360-μ band, and so it is not surprising that the "probable sources" we have observed escaped detection in their survey. The sources previously reported by Friedlander and Joseph (1970) were too weak to have been seen with our degraded sensitivity, and three of those sources lay outside the region covered by the present flight.

To investigate whether our probable sources should appear in the Caltech 2-μ survey (Neugebauer and Leighton 1969), or in surveys carried out at radio wavelengths, we can fit our apparent fluxes with Planck spectra at various temperatures and inquire whether the fluxes at 2 μ and 1 cm would be detectable. For temperatures less than 250° K one finds K-magnitudes considerably fainter than the $K = 4$ limit of the 2-μ survey, and flux densities less than 1 flux unit at 1 cm wavelength. Thus, if the objects we have detected are cool thermal sources, they would not be expected to appear in either the 2-μ or 1-cm surveys.

Artificial satellites will not radiate strongly enough for us to have detected them, and their rapid movement precludes their identification with the class A sources.

Given the $\pm 1°$ positional accuracy for the sources we have detected, it is perhaps unreasonable to expect to discover any *unique* identification with well-known classes of objects, and this expectation has been confirmed by searches of standard catalogs of radio sources, bright galaxies, rich clusters of galaxies, variable stars, near-infrared sources, and H II regions. No associations were found with objects in the AFCRL catalog However, we have found a statistically significant association with nearby stars (Gliese 1969). For five of

TABLE 1

CATALOG OF PROBABLE SOURCES

WU Number	α(1973)	δ(1973)	l^{II}	b^{II}	Type	Number of Observations	Flux (10^{12} W cm^{-2})	Correlated Objects*	Ecliptic Latitude
WU 0138−29.8......	01^h38^m	−29°8	228°5	−79°0	A	2	3	NGC 639, 642; IC 1720; Mar 160; SS Scl, ST Scl; G62	−37°
WU 1059+67.6......	10 59	+67.6	137.7	+46.6	A	2	5	4C+67.18, 4CP 68.12, 4C+68.12, VW UMa; Abl 1166; G406.1	+54°
WU 1428+40.3......	14 28	+40.3	71.7	+65.9	B	2	26	NGC 5625; VV 24; B2-1426+39 A, B2-1426+39 B, B2-1428+39 B, B2-1429+40; OQ 349	+51°
WU 1506+01.2......	15 06	+01.2	0.3	+48.0	A	3	5	NGC 5831, 5839, 5841, 5845, 5846, 5846 A, 5850, 5865, 5868, 5869, 5871; PKS 1505+01, 1509+01; MSH 15+004; 4C+01.41, 00.55, 01.42; OR 010, 009.9, 014.3, 014.9, 016.4, 015.2, HW 5846; W5846; G579.3	+18°
WU 2035−29.3......	20 35	−29.3	14.9	−35.0	A	3	5	IC 5029; PKS 2039−29; OW−253, −260, −360, −263, −265.9; R Mic, RT Mic; Bi 1−582	−10°
WU 2101−24.3......	21 01	−24.3	22.9	−39.1	A	2	4	NGC 7019; OX−202	− 7°
WU 2143+01.0......	21 43	+01.0	57.6	−37.1	B	2	60	IC 1401; IRC 00508; OX 073, 074.9; DU Aqr; Abl 2379, 2373	+14°
WU 2225−30.7......	22 25	−30.7	18.3	−58.5	A	3	5	NGC 7268, 7277; MSH 22−302; G862	−19°
WU 2240−15.9......	22 40	−15.9	47.5	−58.2	A	4	11	IRC−20621; PKS 2241−16; MSH 22−117, 22−118; Bi 8−59	− 7°
WU 2314−08.9......	23 14	−08.9	68.1	−61.0	B	2	7	NGC 7526, 7606; IRC−10567, −10596; G893.2 A,B,C; W7606	− 4°
WU 2338−15.4......	23 38	−15.4	65.3	−69.6	A	2	4	NGC 7717; IRC−20641, −20642 (R Aqr); PKS 2335−14; MSH−119; MWC 400; R Aqr; Bi 11−37 (R Aqr); MS 20 (R Aqr); Abl 2648, 2659	−12°
WU 2357+04.8......	23 57	+04.8	99.8	−55.5	B	2	12	IC 5374, 5375; OZ 092, 093.4, 04.84; Abl 2671	+ 5°

* Abl, Abell (1958); Bi, Bidelman (1954); G, Gliese (1969); HW, Heeschen and Wade (1964); IRC, Neugebauer and Leighton (1969); Mar, Markarian (1972); MWC, Merrill and Burwell (1933, 1943, 1949, 1950); MS, Morrison and Simon (1973); VV, Vorontsov-Veliaminov (1959); W, Wright (1974). Other radio sources from Dixon (1970) except for Ohio sources OX, OZ in Ehman *et al.* (1974).

the 12 objects of table 1 there is a nearby star (nearer than 20 pc) within 1° of the position of the far-infrared object, and within 1°.5 there are eight. Given the relatively small number of stars in this catalog (1049), so many close associations are quite unlikely.[1]

As an example of a possible source model, we note that for a 200° K thermal source at a distance of 1 kpc to produce a flux of 3×10^{-12} W cm^{-2}, the luminosity must be $\sim 3 \times 10^{39}$ ergs s^{-1} and the radius $\sim 5 \times 10^{16}$ cm. These properties are similar to those of the "cocoon" stars discussed by Davidson and Harwit (1967) or some of the late-type stars with extreme infrared excesses such as NML Cyg or VY CMa.

However, the purpose of the present discussion is not to argue strongly for specific models of the sources we have detected, but rather to demonstrate that they very probably are "genuine" celestial objects. The absence of an unequivocal correlation between the sources of table 1 and classes of known celestial objects is extremely interesting, and the situation is not unlike that at similar exploratory stages in radio and X-ray astronomy. The results reported here underscore the importance of further far-infrared surveys off the galactic plane. If confirmed by more extensive observations, these sources may be among the brightest members of a new class of celestial objects.

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REFERENCES

Abell, G. O. 1958, *Ap. J. Suppl.*, No. 31, **3**, 211.
Bidelman, W. P. 1954, *Ap. J. Suppl.*, No. 7, **1**, 175.
Davidson, K., and Harwit, M. 1967, *Ap. J.*, **148**, 443.
Dixon, R. S. 1970, *Ap. J. Suppl.*, No. 180, **20**, 1.
Ehman, J. R. Dixon, R. S., Ramakrishna, C. M., and Kraus, J. D. 1974, *A.J.*, **79**, 144.
Friedlander, M. W., and Joseph, R. D. 1970, *Ap. J. (Letters)*, **162**, L87.
Gliese, W. 1969, *Veröff. Astr. Rechen-Inst. Heidelberg*, No. 22.
Heeschen, D. S., and Wade, C. M. 1964, *A.J.*, **69**, 277.
Hoffmann, W. F., and Frederick, C. L. 1969, *Ap. J. (Letters)*, **155**, L9.
Hoffmann, W. F., Woolf, N. J., Frederick, C. L., and Low, F. J. 1967, *Science*, **157**, 187.
Joseph, R. D. 1974, *J. Phys. E* (submitted for publication).
Markarian, B. E. 1972, *Astrofisika*, **8**, 89.
Merrill, P. W., and Burwell, C. G. 1933, *Ap. J.*, **78**, 87.
———. 1943, *ibid.*, **98**, 153.
———. 1949, *ibid.*, **110**, 387.
———. 1950, *ibid.*, **112**, 72.
Morrison, D., and Simon, T. 1973, *Ap. J.*, **186**, 193.
Neugebauer, G., and Leighton, R. B. 1969, *Two-Micron Sky Survey: A Preliminary Catalog* (NASA SP-3047) (Washington: Government Printing Office).
Vorontsov-Veliaminov, B. 1959, *Catalogue of Interacting Galaxies* (Moscow).
Wright, A. E. 1974, *M.N.R.A.S.*, **167**, 251.

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[1] *Note added in proof.*—It is also possible that many of the "probable sources" are in the solar system. One-third of them lie within ± 7° of the ecliptic, and three-fourths are within ±20°