THE ASTRONOMICAL JOURNAL VOLUME 85, NUMBER 12 DECEMBER 1980

# HIGH-FREQUENCY STRUCTURE OF OOTY OCCULTATION SOURCES. II

T. K. MENON

Department of Geophysics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1W5, Canada

*Received 18 August 1980*

## ABSTRACT

A sample of 57 sources from the Ooty Lunar Occultation survey at 327 MHz has been studied using the 3-element interferometer system at Green Bank at frequencies 2.7 and 8.1 GHz. A comparison of the angular separation at low and high frequencies for well resolved double sources does not show any frequency-dependent effects. The mean spectral index of the 42 doubles in the sample is 0.92, considerably steeper than the usual mixed samples. The source 1417−19 is found to be a triple source, with a strong central component coinciding with the N galaxy suggested as the identification.

## I. INTRODUCTION

The lunar occultation observations, using the Ooty Radio Telescope, have provided us with high-resolution structural information at 327 MHz for over 1000 weak radio sources. As part of a program to study the spectra of components of these sources, a large number of them were observed with the 3-element interferometer at Green Bank at 2.7 and 8.1 GHz simultaneously. In two earlier papers (Menon 1975, 1976), the structures of six sources, which have prominent central components in addition to two or more extended components, were discussed. In this paper I shall discuss the structures and spectra of 57 sources. The majority of the present sources appear to have simple double structures, with a few which could be represented by triple and head-tail structures.

## II. OBSERVATIONS

The sources were observed in the interferometer configuration 900-1800-2700 m or 800-1900-2700 m at both 2.7 and 8.1 GHz. The basic reduction procedures were the same as described in Menon (1976). Because of the incomplete baseline coverage of the observations, the parameters of the source components were determined by a model-fitting program. In this paper I shall discuss mostly comparisons of the occultation and interferometer positions and total sizes, since the component sizes are highly model dependent. Single dish measurements of most of the sources were made at 1.4 and 2.7 GHz using the 300-ft telescope at Green Bank.

## III. DISCUSSION

The basic data for the sources are given in Tables I–III. I shall first discuss the interesting aspects of a number of sources and then compare the parameters derived from the occultation and interferometer measurements. The references to various occultation lists are given at the end of Table III.

*0011+054*. The L.O. and INT positions agree very well and component B appears to have a flatter spectrum than component A. Smallest resolved double in the present survey.

*0023+058*. One of the weakest unresolved sources with a positive identification.

*0042+082* and *0042+084*. Both sources are clear doubles at 2.7 GHz. The centroid of 0042+082 agrees very well with the L.O. position. But the centroid of 0042+084 differs by more than 15″ from the L.O. position. These two sources are the weakest doubles observed in the present program and have angular sizes of 13″ and 15″, respectively. Both sources are within the cluster Zw 0042.5+0824.

*0327+241*. The 8.1-GHz position agrees exactly with that of a $17.5^{m}$ galaxy suggested by Kapahi *et al.* (1973) as the identification for the source. The 2.7-GHz data suggest outer structure for the source.

*0327+246*. This source has recently been observed by Owen *et al.* (1977) at 2.7 GHz. My 2.7-GHz data agree very well with their data. The contours have the appearance of a head-tail source. However, my 8-GHz data suggest that the head consists of at least two components, of which the position of the brighter component coincides with the brightest galaxy in the Abell cluster 0439.

*0435+270*. The interferometer data show only one component which does not coincide with either of the L.O. components.

*0437+273*. The source has a spectral index of 0.22 and its position coincides exactly with an 18.5-mag galaxy.

*0516+276*. L.O. data show complex structure with most of the emission confined to a region of diameter 60″ and a possible halo up to 2 arcmin. The 2.7-GHz structure has a maximum flux density of only 0.33 Jy, and at 8.1 GHz the flux density is about 0.22 Jy. This may be compared to the single dish flux densities of 1.1 and 0.59 Jy. Kapahi *et al.* (1973) suggested a pair of 18-mag galaxies (about 7 arcsec apart) lying close to the radio centroid as the optical identification for the source. The

TABLE I. Double sources.

| Source | List No. | Flux at 327 MHz (Jy) | Spectral index | θ″ L.O. | θ″ INT | ΔP.A. (deg) | Notes |
|---|---|---|---|---|---|---|---|
| 0011+054 | 3 | 4.2 | 0.83 | 3.5 | 4.1 | 3.0 | N |
| 0042+082 | 4 | 0.3 | 0.85 | | 13.2 | | N |
| 0042+084 | 4 | 0.3 | 0.72 | | 15.0 | | N |
| 0150+164 | 1 | 1.9 | 0.98 | 8.0 | 9.0 | 0 | |
| 0301+194 | 8 | 1.1 | 1.38 | 14.4 | 10.8 | 9.0 | |
| 0328+248 | 3 | 1.4 | 1.00 | 6.5 | 6.1 | 22.5 | |
| 0334+220 | 7 | 1.3 | 0.98 | 53.0 | 52.0 | 16.0 | |
| 0532+281 | 5a | 1.1 | 0.81 | 13.0 | 13.0 | 0 | N |
| 0557+221 | 8 | 1.6 | 0.83 | 25.0 | 21.0 | 6.0 | |
| 0604+266 | 4 | 3.7 | 0.90 | 60.0 | 88.0 | 17.0 | |
| 0609+276 | 5a | 0.8 | 0.99 | 12.0 | 12.0 | 8.0 | |
| 0619+266 | 3 | 1.9 | 0.86 | 6.5 | 4.0 | 7.0 | |
| 0710+257 | 3 | 1.4 | 1.00 | 17.0 | 20.0 | 6.0 | |
| 0713+196 | 8 | 1.7 | 1.06 | 31.0 | 32.0 | 3.0 | |
| 0805+225 | 3 | 1.5 | 0.87 | 15.0 | 15.0 | 22.0 | |
| 0818+217 | 5a | 0.7 | 1.03 | 22.0 | 29.0 | 18.0 | |
| 0836+195 | 6 | 1.3 | 0.89 | 13.0 | 13.0 | 7.0 | |
| 0848+181 | 3 | 1.0 | 1.09 | 16.0 | 14.0 | 11.0 | |
| 0851+143 | 5b | 6.2 | 0.77 | 5.0 | 6.0 | 3.5 | N |
| 0856+170 | 3 | 2.3 | 0.92 | 9.0 | 10.0 | 2.0 | |
| 0907+185 | 5a | 2.0 | 0.75 | 38.5 | 41.0 | 0 | N |
| 0911+174 | 3 | 5.0 | 0.87 | 46.0 | 51.0 | 1.6 | |
| 0943+123 | 6 | 1.5 | 0.64 | 12.0 | 13.0 | 7.0 | N |
| 1023+078 | 3 | 1.9 | 0.96 | 10.0 | 12.0 | 0 | |
| 1104+058 | 3 | 2.0 | 0.92 | 8.0 | 13.0 | 12.0 | N |
| 1107+036 | 6 | 1.8 | 0.90 | 64.0 | 63.0 | 2.0 | |
| 1142−002 | 4 | 3.0 | 0.91 | 29.0 | 29.0 | 0 | |
| 1225−083 | 6 | 1.7 | 0.79 | 14.0 | 10.5 | 7.0 | N |
| 1302−112 | 4 | 1.1 | >0.8 | 33.0 | 28.0 | 18.0 | |
| 1310−133 | 6 | 1.6 | 0.86 | 35.0 | 33.0 | 12.0 | |
| 1354−176 | 4 | 2.4 | 0.84 | 10.0 | 9.0 | 8.0 | N |
| 1417−192 | 5a | 5.5 | 0.79 | 55.0 | 63.0 | 18.0 | N |
| 1527−242 | 1 | 0.8 | 0.79 | 21.0 | 25.0 | 6.0 | |
| 1628−268 | 5a | 8.0 | >1.10 | 105.0 | 91.0 | 0 | N |
| 1709−281 | 5a | 13.0 | 0.72 | 15.0 | 14.0 | 5.0 | |
| 1713−279 | 6 | 0.6 | 1.00 | 35.0 | 35.0 | 7.0 | |
| 1912−269 | 4 | 6.3 | >1.20 | 46.0 | 45.0 | 8.0 | |
| 1932−190 | 8 | 1.7 | 1.07 | 6.0 | 7.0 | 6.0 | N |
| 2006−238 | 4 | 0.7 | 1.06 | 17.0 | 13.0 | 4.0 | |
| 2053−201 | 4 | 5.6 | 0.67 | 27.0 | 35.0 | 19.0 | N |
| 2057−179 | 5a | 2.2 | 1.11 | 10.0 | 9.0 | 1.5 | |
| 2120−166 | 5a | 6.0 | 1.07 | 10.0 | 15.0 | 10.0 | N |

interferometer position coincides with that of the northern galaxy of the pair to within (+2″,0.7″). The interferometer contours show an extension toward south in the direction of the other galaxy, which is closer to the L.O. position. The total spectral index of the source is 0.64 and the source is best represented by a flat-spectrum central component of the northern galaxy surrounded by an extended halo.

*0532+281*. The L.O. position angle was unfavorable with respect to the orientation of the double source. The second alternative suggested in list 5 agrees exactly with the interferometer data.

*0706+261*. The source has a spectral index of 0.66 and is not resolved, even at 8.1 GHz. Position coincides with the suggested identification.

*0815+229*. The source is marginally resolved at 8.1

TABLE II. Single sources.

| Source | List No. | Flux at 327 MHz (Jy) | Spectral index | θ | Δα L.O. − INT | Δδ L.O. − INT | Identification | Notes |
|---|---|---|---|---|---|---|---|---|
| 0023+058 | 5a | 0.6 | 0.76 | <3″ | +0.07$^s$ | +2″ | BO | N |
| 0327+241 | 3 | 1.8 | 0.85 | cx | −0.43 | +3.1 | G | N |
| 0435+270 | 4 | 0.6 | 1.18 | | −0.36 | +2.8 | EF | N |
| 0437+273 | 4 | 0.4 | 0.22 | <8″ | 0 | +1.0 | G | N |
| 0706+261 | 5a | 2.5 | 0.66 | <3″ | −0.09 | +1.2 | RO | N |
| 0815+229 | 4 | 0.6 | 0.81 | ∼10″ | 0 | +4.0 | G | N |
| 1123+012 | 5a | 1.2 | 0.80 | ∼2″ | 0 | 0 | G | N |
| 1640−231 | 8 | 1.75 | 0.30 | | −0.14 | +6.6 | BSO | N |
| 2034−198 | 5a | 0.8 | 0.63 | <2″ | −0.03 | −3.0 | G | N |
| 2040−219 | 4 | 1.3 | 0.97 | cx | +0.36 | +2.0 | G | N |
| 2042−212 | 4 | 0.6 | 0.82 | ∼8″ | +0.07 | +4.0 | G | N |

TABLE III. Complex sources.

| Source | List No. | Flux at 327 MHz (Jy) | Spectral index | Notes |
|---|---|---|---|---|
| 0327+246 | 3 | 1.2 | 0.85 | N |
| 0516+276 | 3 | 4.4 | 0.64 | N |
| 0914+175 | 4 | 1.2 | 0.83 | N |
| 2058−179 | 5a | 3.0 | 0.78 | N |

List sources for Tables I–III

List 1. Swarup, G., *et al.* (1971). Astrophys. Lett. **9**, 53.
List 3. Kapahi, V. K., *et al.* (1973). Astron. J. **78**, 673.
List 4. Joshi, M. N., *et al.* (1973). Astron. J. **78**, 1023.
List 5a. Kapahi, V. K., *et al.* (1974). Astron. J. **79**, 515.
List 5b. Joshi, M. N., and Gopal-Krishna. (1977). Mon. Not. R. Astron. Soc. **178**, 717.
List 6. Subramanya, C. R., and Gopal-Krishna. (1980). Mem. Astron. Soc. India (in press).
List 7. Singal, A. K., *et al.* (1979). Mem. Astron. Soc. India **1**, 14.
List 8. Venkatakrishna, K. L., and Swarup, G. (1979). Mem. Astron. Soc. India **1**, 25.

GHz with an extension toward P.A. = 0°. The suggested identification appears to be a galaxy with a dark band.

*0851+143.* The L.O. data and the 8.1-GHz data suggest that the source could be either a head-tail source or an unequal double separated by 6 arcsec.

*0907+185.* Remarkable equal double over the frequency range from 327 MHz to 8.1 GHz. Component A is exactly at the position tentatively suggested by the L.O. data. Three objects close together are at the center of the double.

*0914+175.* The source is extended to the south at 2.7 GHz and has a steep gradient to the north and has a steep spectral index. Could be a head-tail type of galaxy.

*0943+123.* Position of component A agrees very well with the suggested optical identification.

*1104+058.* The suggested optical identification is exactly at the center of the two 2.7-GHz components.

*1123+012.* The 8.1-GHz contours suggest that the source is probably extended in the same position angle as noted in the L.O. data. The position of the peak agrees with that of a 20-mag galaxy in cluster Zw 1123.6+0118.

*1225−083.* The L.O. data show a double with separation of 14″ in P.A. = 103°. However, at 2.7 and 8.1 GHz the source is seen to be a double with a separation of 9″ in P.A. 96°. The coordinates of component B agree with each other at all frequencies. However, there does not appear to be a counterpart of L.O. component A in the interferometer data. The strongest 8.1-GHz component coincides exactly with the 18.5-mag N galaxy suggested as the optical identification by Subramanya (1978). It is likely that the source is a triple source with the central component dominating at high frequencies.

*1354−176.* The source is seen to be a simple double at 2.7 GHz but the declinations of both components are about 5″ lower than those of the L.O. positions. At 8.1 GHz each of the above two components may be double sources.

*1417−19.* The data from five occultations were interpreted by Kapahi *et al.* (1974) as that of a source in which 55% of the total flux density was in a "head" component A, which has an angular size of the order of 7.5 × 4 arcsec with its major axis in P.A. 145° ± 10°. The remaining flux density was suggested to be in a "tail" that extended to nearly 60 arcsec northeast along P.A. 30° ± 10°. The source had been identified with a 17.3-mag N galaxy by Bolton and Ekers (1966) on the basis of a position measurement at 2.7 GHz. The redshift of the galaxy was measured by Burbidge (1967) to be 0.1192. The occultation components do not coincide with the optical position of the galaxy (see Fig. 1). At 2.7 GHz the source consists of three components, whose positions are given in Table I along with the occultation position of component A and the optical position of the galaxy. From the limited baseline data it can also be inferred that component C is highly resolved, that component A is partially resolved at 8.1 GHz, and that component B is unresolved. The occultation and interferometer positions of component A agree very well. The position of component B agrees with that of the galaxy.

The spectral index of the whole source is found to be about 0.79, while that of the components A and C are respectively about 0.86 and 1.0. The spectral index of component B is about 0.1 between 2.7 and 8.1 GHz. A recent reanalysis of the occultation data by Subramanya (private communication) using his Optimum Deconvolution Method suggests that even at 327 MHz there is a central component at the position of the galaxy with about 23% of the total flux density at that frequency. The spectral index of B varies from about 0.75 at low frequencies to about 0.1 at high frequencies. Such a change in spectral index generally implies that in addition to the compact component there is also an extended component. A number of sources with compact central components for which high-resolution observations are available at low and high frequencies (see Joshi and Gopal-Krishna 1977, Menon 1975, 1976, and Bridle and Fomalont 1978) show that the occurrence of an extended central component surrounding a compact central component in both galaxies and quasars is not uncommon. Recently Bridle and Fomalont (1978) have suggested, from an investigation of 48 extended radio galaxies, that two classes of central components occur in these galaxies. Those which have been resolved and have spectral indices $\alpha > 0.4$ are classified by them as extended cores and those with $\alpha < 0.4$ as compact cores. The observations of Bridle and Fomalont (1978) were carried out at 2.7 and 8.2 GHz, and hence they had no information about the spectra of the compact cores at low frequencies. However, as noted above, whenever high-resolution, high-sensitivity data are available, the compact core sources are found to have steep-spectra extended components surrounding them. It would be extremely interesting to find out whether the extended

TABLE IV. Positions and flux densities of components of PKS 1917−19.

| Component | R.A.(1950) | Decl.(1950) | Spectral index |
|---|---|---|---|
| A | $14^h17^m02\overset{s}{.}44 \pm 0\overset{s}{.}07$ | $-19°15'09\overset{''}{.}3 \pm 0.5$ | 0.86 |
| B | $14^h17^m02\overset{s}{.}65 \pm 0\overset{s}{.}07$ | $-19°14'41\overset{''}{.}3 \pm 0.5$ | 0.75 to 0.1 |
| C | $14^h17^m03\overset{s}{.}35 \pm 0\overset{s}{.}07$ | $-19°14'07\overset{''}{.}3 \pm 1.0$ | 1.00 |

central component is elongated in the direction of the axis of the double source as is found in the case of the extended cores of Cyg A and 3C 154. The linear sizes of these components are of the order of a few kiloparsec as compared to a few parsec or less for the compact components. The very existence of an extended and elongated central component has important implications for theories of the origin and mode of energy supply for double radio sources.

A number of N galaxies have been found by Marshall *et al.* (1978) to be x-ray sources. For these sources the x-ray luminosities are found to be closely related to the radio frequency flux density of the compact components at their center. The flux density of the compact central component of PKS 1417−19 at 5 GHz is nearly 60% of that of the compact component of 3C 382. This latter source is one of the strongest x-ray sources in the list of Marshall *et al.* (1978), and hence the source PKS 1417−19 is also likely to be a strong x-ray source (see Table IV).

*1628−268.* In the L.O. data the source has a strong core and an extended tail in P.A. 103°. At 2.7 GHz the source is double in P.A. 103° and separation 91″, compared to the extent of 105″ for the tail. Hence the structures are comparable. It is possible that the L.O. data are affected by ionospheric scintillation. At 8.1 GHz, component A itself is resolved and consists of two components in P.A. 143°. The L.O. data also show that component A is extended.

*1640−232.* The source is found to be a double at 327 MHz. But at both 2.7 and 8.1 GHz, the source is single with a nearly flat spectrum.

1932−190. At 2.7 GHz the source appears to be triple.

*2034−198.* Position coincides exactly with the suggested identification of an 18th-mag galaxy.

*2040−219.* Position coincides with an 18th-mag galaxy.

*2042−212.* Position coincides with an 18th-mag galaxy.

*2053−201.* The source is a double with a separation of 35″ in P.A. 33°. The agreement with L.O. data is not good. But the E galaxy identified by Bolton *et al.* (1965) with the source falls exactly at the middle of the interferometer components.

*2058-179.* The source at 2.7 GHz is elongated, almost as a double, in P.A. 153°, very similar to the L.O. data. But at 8.1 GHz only one component is seen, which coincides exactly with a 19.5 BSO suggested by Kapahi *et al.* (1974) as the identification. Possibly a D2-type QSO.

*2120−166.* At 8.1 GHz component A is definitely extended and complex. The peak of the component is displaced toward component B and hence may be a central component of a triple source.

The information about the structure of sources obtained from lunar occultation observations is necessarily influenced by the random position angles of occultation with respect to the true structure of the sources. Since in most cases I am able to obtain information in at least two position angles of occultation, the basic structure,

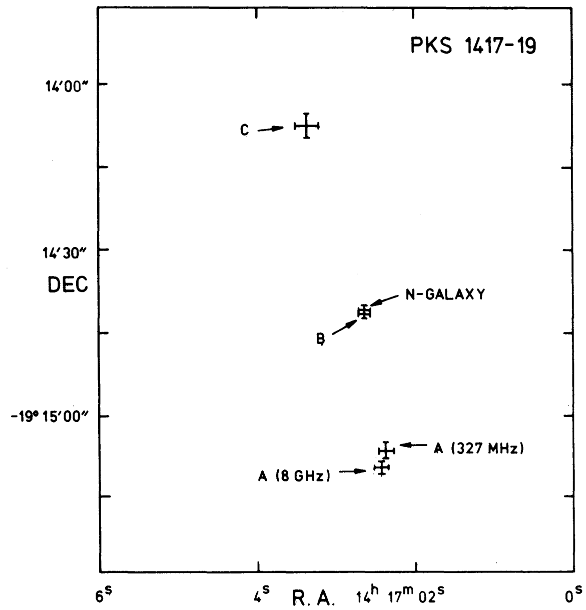


FIG. 1. Positions of components of PKS 1417−19.

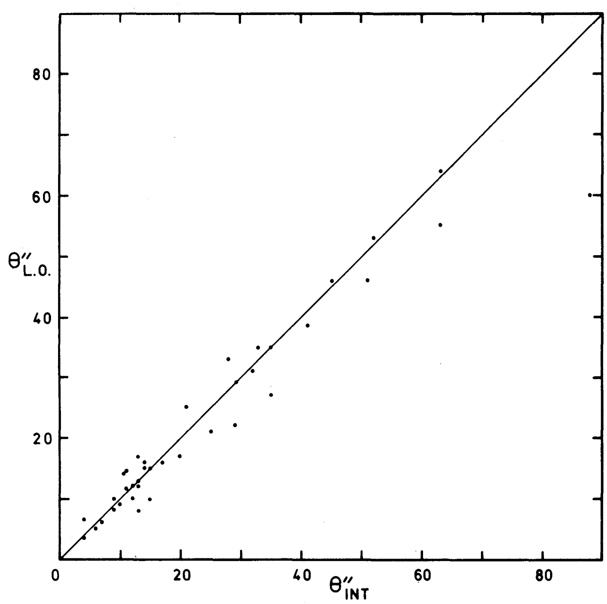


FIG. 2. Comparison of occultation and interferometer sizes.

such as a double or unresolved, can be reliably determined. A comparison of the occultation data and the interferometer data for double sources in Table I shows that there is fairly good agreement between the position angles of the main structure of a source determined by the two methods. In cases where there are significant discrepancies, I can trace them either to an unfavorable position angle of the occultation for a particular source or to low signal-to-noise ratio.

One of the motivations in undertaking the high-frequency observations of Ooty sources was to determine whether there is any dependence of the angular size on frequency. Such a dependence is to be expected if there are systematic variations of spectral indices as a function of the distance from the center of the source. The same effect can also be produced if the components consist of a dominant flat-spectrum compact head surrounded by a steep-spectrum halo elongated in the direction of the center of the source. Jenkins and Scheuer (1976) and Gopal-Krishna and Swarup (1977) have compared the high- and low-frequency structures of a number of sources. In general, they do not find any systematic difference in the positions of the extended components at the two frequencies. I have plotted in Fig. 2 the angular separations of well resolved doubles from the occultation and the interferometer data. For the vast majority of the sources, where the instrumental resolutions are comparable the two values agree reasonably well. For the few sources for which the high-frequency separations appear to be larger than the low-frequency separations, the occultation resolution has been affected by ionospheric scintillations. Hence one may conclude that for purposes of measurement of total angular extents, the low-frequency occultation data provide adequate information and that there are no systematic effects of frequency on angular separations of double sources.

The mean spectral index between 327 MHz and 2.7 GHz of all the double sources in the present sample is 0.92, and only nine of the spectral indices are below 0.8. It is generally recognized that any flattening of the spectrum at the high frequencies is due to the presence of one or more flat spectral index central components which dominate at high frequencies. The spectral index distribution of sources can, therefore, be used to estimate the initial luminosity function of radio sources in a manner similar to the derivation of the Salpeter luminosity function of stars. This question will be discussed elsewhere.

I am grateful to the Director of the National Radio Astronomy Observatory for allocating the observing time needed for the observations discussed in this paper. The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation. This work has been partially supported by a grant from the Natural Sciences and Engineering Research Council of Canada.

## REFERENCES

Bolton, J. G., Clarke, M. E., and Ekers, R. D. (1965). Aust. J. Phys. **18,** 627.

Bolton, J. G., and Ekers, J. (1966). Aust. J. Phys. **19,** 559.

Bridle, A. H., and Fomalont, E. B. (1978). Astron. J. **83,** 704.

Burbidge, E. M. (1967). Astrophys. J. **149,** L51.

Gopal-Krishna, and Swarup, G. (1977). Mon. Not. R. Astron. Soc. **178,** 265.

Jenkins, C. J., and Scheuer, P. A. G. (1976). Mon. Not R. Astron. Soc. **174,** 327.

Joshi, M. N., and Gopal-Krishna. (1977). Mon. Not. R. Astron. Soc. **178,** 717.

Kapahi, V. K., Joshi, M. N., Subramanya, C. R., and Gopal-Krishna. (1973). Astron. J. **78,** 673.

Kapahi, V. K., Joshi, M. N., and Sarma, N. V. G. (1974). Astron. J. **79,** 515.

Marshall, F. E., Mushotzky, R. F., Boldt, E. A., Holt, S. S., Rothschild, R. E., and Serlemitsos, P. J. (1978). Nature **275,** 624.

Menon, T. K. (1975). Astrophys. J. **199,** L161.

Menon, T. K. (1976). Astrophys. J. **204,** 717.

Owen, E. N., Rudnick, L., and Peterson, B. M. (1977). Astron. J. **82,** 677.

Subramanya, C. R. Private communication.

Subramanya, C. R. (1978). Ph.D. thesis, Bombay University (unpublished).