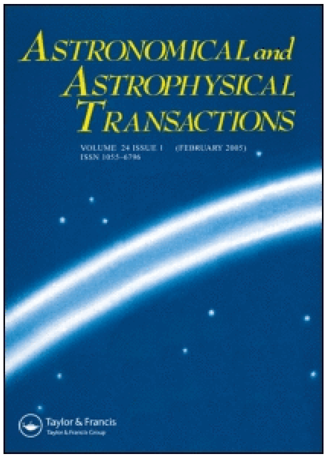
This article was downloaded by:[Bochkarev, N.]
On: 20 December 2007
Access Details: [subscription number 788631019]
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954
Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Asymmetry in the variability of radio sources towards the centre and anti-centre of the galaxy

N. Y. Shapirovskaya [a]; O. B. Slee [b]; G. S. Tsarevsky [a]
[a] Astro-Space Centre, Lebedev Physical Institute, Russian Academy of Sciences, Russia
[b] Australia Telescope National Facility, Epping, Australia

Online Publication Date: 01 April 1995

To cite this Article: Shapirovskaya, N. Y., Slee, O. B. and Tsarevsky, G. S. (1995) 'Asymmetry in the variability of radio sources towards the centre and anti-centre of the galaxy', Astronomical & Astrophysical Transactions, 7:1, 47 - 56
To link to this article: DOI: 10.1080/10556799508203253
URL: http://dx.doi.org/10.1080/10556799508203253

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article maybe used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Astronomical and Astrophysical Transactions, 1995,
Vol. 7, pp. 47–56
Reprints available directly from the publisher.
Photocopying permitted by license only

©1995 OPA (Overseas Publishers Association)
Amsterdam B.V. Published under license by
Gordon and Breach Science Publishers SA
Printed in Malaysia

ASYMMETRY IN THE VARIABILITY OF RADIO SOURCES TOWARDS THE CENTRE AND ANTI-CENTRE OF THE GALAXY

N. Y. SHAPIROVSKAYA[1], O. B. SLEE[2], and G. S. TSAREVSKY[1]

[1] *Astro-Space Centre, Lebedev Physical Institute, Russian Academy of Sciences, 17324 Moscow, Leninsky Pr. 53, Russia*
[2] *Australia Telescope National Facility, PO Box 76, Epping, NSW 2121, Australia*

(Received August 30, 1993; revised May 2, 1994)

We report an asymmetry in the distribution of low frequency variable (LFV) radio sources towards the centre-anticentre regions of our galaxy. The study is based on 15 years' monitoring of a large sample of sources observed with Culgoora Array at 80 and 160 MHz. This asymmetry is in marked contrast with the symmetrical distribution of non-variable sources from the same sample. Median values of the corresponding modulation indices on both short and long time scales also show a statistically significant increase towards the Galactic centre compared with the anticentre region.

These results strongly suggest that LFV has an interstellar origin and that the most likely mechanism is refractive scintillation.

KEY WORDS Extra-galactic radio sources, radio source variability, interstellar matter

1 INTRODUCTION

The low frequency variability (LFV) of extra-galactic radio sources (at frequencies < 1 GHz) has yet to be simply explained. Searches for LFV in the range 80–1000 MHz have been made by several observers including Hunstead (1972), Cotton *et al.* (1979), Fisher and Erickson (1980), Fanti *et al.* (1981), McAdam (1982), Altschuler *et al.* (1984), Slee and Siegman (1988) and Spangler *et al.* (1989).

A wide range of theoretical models has been proposed to account for LFV. The interpretation of the LFV mechanism in terms of intrinsic variations in emitted power has encountered some serious difficulties. The main contradiction between observations and the "canonical" extragalactic sources model is that the time-scale of LFV (month to years) is considerably shorter than the upper limit provided by the linear size of the source divided by the speed of light. For this reason some exotic mechanisms have been advanced to explain "superluminal" LFV, some of which are:

1. Relativistic bulk motion of the emitting plasma.
2. Ultra-bright non-thermal emission mechanisms producing $T_b > 10^{12}$ K.
3. Non-cosmological red shifts.

An alternative explanation of LFV, first proposed by Shapirovskaya (1978), was the suggestion that the intensity variations are scintillations caused by scattering or refraction by large-scale turbulence in the ionized interstellar gas with scale 10^{13}–10^{14} cm. Later, Rickett *et al.* (1984) have attributed the LFV of extragalactic sources as well as the long-term fading of pulsars to essentially refractive scintillations.

Some observational evidence that propagation phenomena through the interstellar medium are at least partially responsible for LFV was presented by Gregorini *et al.* (1986) and by Cawthorne and Rickett (1985). However, the earlier analysis of large LFV samples did not come to a clear conclusion about the nature of the variability (Slee and Siegman, 1988; Spangler *et al.*, 1989).

We have performed a statistical analysis of the results of a long time series of flux density measurements of 412 radio sources presented by Slee and Siegman (1988; hereafter referred to as SS88). We found that there is significant evidence that at least a considerable part of LFV may be a result of interstellar propagation effects. We have made our study on the premise that the interstellar medium is heterogeneous not only in galactic latitude but also in longitude (Rao and Ananthakrishnan, 1984; Cordes *et al.*, 1985; Alurkar *et al.*, 1986; Shapirovskaya and Bocharov, 1989) and therefore it is reasonable to expect a significant difference in the interstellar turbulence in the opposite directions – towards the centre and anticentre of the Galaxy.

2 SELECTION OF THE SAMPLE

SS88 chose their sample of 412 radio sources from about 2500 sources that had been observed with the Culgoora circular array at 80 and 160 MHz between 1970 and 1984. These sources are listed in Slee and Higgins (1973, 1975), Slee (1977) and Slee and Siegman (1983).

The observations were made in the drift-scan mode, which is described in detail in the above papers. Ionospheric refraction changes increased the width of the profiles and consequently increased the error in the estimate of flux density. The state of the ionosphere was assessed by three-hourly observations of flux calibrators and the occasional stronger target sources, whose drift profiles were displayed in real time. No observations were made if the ionosphere was strongly disturbed. Each observation resulted in an averaged drift profile of width in both coordinates < 1.07 times than expected from a point source. This criterion ensures that the flux-density error due to refractive widening was negligible but it also resulted in the rejection of all sources with intrinsic angular diameters > 1.4 arcmin at 80 MHz and > 0.7 arcmin at 160 MHz.

The final sample selected by SS88 is a random one in the sense that it was not based on flux density, radio spectrum, previous variability studies, optical identification or coordinates.

The following conclusions from SS88 would be worth to remind here:

(i) 47 percent and 27 percent of the sample display variability at the 95% and 99% confidence level, respectively.

(ii) Sources with flatter spectra tend to be more variable than steeper spectrum ones.

(iii) Sources with lower galactic latitudes are more variable than their higher-latitude counterparts.

In this paper we extend the analysis of SS88 to an investigation of the effects of galactic longitude on metre wavelength variability.

3 METHOD AND RESULTS OF DATA ANALYSIS

3.1 Centre - Anticentre Distributions

We have determined the number of sources (treating the 80 and 160 MHz measurements separately) in the following directions:

(C) in the longitude sector towards the Galactic centre (l between 285 and 75°), 208 variable and non-variable sources;

(AC) in the longitude sector towards the anticentre (l between 105° and 255°), 176 variable and non-variable sources.

The sources located in the two 30°-wide boundary sectors between C and AC have been excluded in order to provide a clearer division between the centre and anticentre sources.

In addition, the sources at each frequency were subdivided into subsamples that took account of whether the sources were variable on time-scales of one month (m_1), 12 months (m_{12}) or on both (designated "all" in Tables 1a and 1b). A further sub-sample consisted of sources showing one-monthly variability and included the sources at both frequencies. The results are given in Table 1a, which shows the number of the radio sources in each of the sub-samples in the centre (N_C) and anticentre (N_{AC}) sectors, and the ratio of these numbers in the column five. The sub-samples with the designation "99%" refer to those sources that are variable at $>$ 99 percent confidence level. The "all" sub-samples contain sources that are variable at $>$ 95 percent confidence.

At this stage, we merely note that the ratio N_C/N_{AC} averages about 1.5 over all the sub-samples of variable sources, while the ratio is unity for the non-variable category. The significance of these figures will be discussed later.

Table 1a. Number of radio sources in the centre and anticentre sectors

Sample (all $\|b\|$)	*Subsample*	*Number of sources* *Centre* N_C	*Anticentre* N_{AC}	*Ratio* N_C/N_{AC}	χ^2	*Probability* P
Non-variable	All	98	96	1.0	–	–
	All	50	38	1.3	0.96	0.16
Variable	m_1(all)	46	31	1.5	1.88	0.08
at 80 MHz	m_1(99%)	28	19	1.5	1.24	0.13
sources	m_{12}(all)	21	16	1.3	0.48	0.25
	m_{12}(99%)	11	9	1.2	0.15	0.35
	All	60	42	1.4	1.85	0.09
Variable	m_1(all)	50	35	1.4	1.64	0.10
at 160 MHz	m_1(99%)	38	22	1.7	3.03	0.04
sources	m_{12}(all)	35	21	1.7	2.51	0.05
	m_{12}(99%)	17	10	1.7	1.47	0.11
Variable at 80 and 160 MHz sources	All	16	7	2.3	2.99	0.04

Key to the subsamples:

All – all sources in a sample;

m_1(all) – all sources with 1-monthly variability;

m_{12}(all) – all sources with 12-monthly variability;

m_1(99%) – sources with 1-monthly variability at the 99 percent confidence level.

Table 1b. Number of radio sources in the centre and anticentre sectors with galactic latitude less than 30 deg

Sample ($\|b\| < 30°$)	*Subsample*	*Number of sources* *Centre* N_C	*Anticentre* N_{AC}	*Ratio* N_C/N_{AC}	χ^2	*Probability* P
Non-variable	All	32	32	1.0	–	–
	All	21	12	1.8	1.63	0.10
Variable	m_1(all)	17	8	2.1	2.35	0.06
at 80 MHz	m_1(99%)	12	4	3.0	3.23	0.03
sources	m_{12}(all)	11	7	1.6	0.70	0.20
	m_{12}(99%)	7	3	2.3	1.39	0.12
	All	27	22	1.2	0.30	0.29
Variable	m_1(all)	25	17	1.5	0.93	0.16
at 160 MHz	m_1(99%)	21	11	1.9	2.11	0.07
sources	m_{12}(all)	16	12	1.3	0.40	0.26
	m_{12}(99%)	10	6	1.7	0.80	0.18
Variable at 80 and 160 MHz sources	All	8	2	4.0	3.13	0.04

Table 2. Median modulation indices of the LFV sources in the centre and anticentre regions (with galactic latitude less than 30 deg.)

Sample ($\|b\| < 30°$)	*Subsample*	*Median mod. indices and mean*						χ^2	*P*
		Centre			*Anticentre*				
		m	$\langle\|b\|\rangle$	*S.E.*	m	$\langle\|b\|\rangle$	*S.E.*		
Variable at 80 MHz	m_1	0.19	18°	2°	0.14	13°	3°	1.22	0.13
	m_{12}	0.34	16	2	0.23	12	3	0.34	0.28
Variable at 160 MHz	m_1	0.24	18	2	0.15	14	2	7.52	0.003
	m_{12}	0.33	22	2	0.26	18	3	0.74	0.19
Variable at 80 and 160 MHz	$m_1(80)$	0.14	15	3	0.08	13	2	7.37	0.003
	$m_1(160)$	0.24	15	3	0.10	13	2	1.63	0.10

Key to headings:
m_1 – all sources with 1-monthly variability;
m_{12} – all sources with 12-monthly variability;
$m_1(80)$—1-monthly 80 MHz variability for the sources variable at 80 and 160 MHz;
$m_1(160)$ – 1-monthly 160 MHz variability for the sources variable at 80 and 160 MHz;
$\langle|b|\rangle$ – average galactic latitude;
S.E. – standard error in $\langle|b|\rangle$.

Table 1b is similar in form to Table 1a except that the sub-samples consist of sources with $|b| < 30°$. We point out that the ratios N_C/N_{AC} for the lower-latitude sources generally exceed those for all latitudes in Table 1a.

We present the difference between centre and anti-centre source variability in an alternative way in Table 2, which shows the median modulation indices (as defined by SS88) for the sources with $|b| < 30°$. The mean galactic latitude of each sub-sample is shown, since it is possible that relatively small changes in latitude may affect the variability significantly (selection effect, see SS88). It is seen that these values do not differ within standard errors for each centre-anticentre pair of the sub-samples.

3.2 Statistical Analysis

The ratios N_C/N_{AC} in Tables 1a, b were tested for significance by constructing 2x2 contingency tables (see Sachs, 1972). It should be noted that data normalization was performed under this test to account for an initial Centre-Anticentre asymmetry. The results are presented in the last two columns, which list the χ^2 value and chance probability of to each ratio (one-sided criteria). We can see that, for several sub-samples in Table 1a, the ratios have low probabilities of chance occurrence, especially for the 160 MHz measurements.

Since 80 MHz and 160 MHz measurements were made independently, we suggest their weak correlation and therefore can pool the probabilities for the same sub-samples at the two frequencies. Thus, for example, for the m_1 sub-samples, the probability that the measured ratios N_C/N_{AC} obtained at *both* frequencies will occur by chance is $0.08 \times 0.10 = 0.008$. Therefore, when the results are pooled at two frequencies, all the sub-samples show significantly more variable sources in the Galactic centre sector. Similar conclusions apply to the sources with $|b| < 30°$, despite the lower numbers of sources in the sub-samples of Table 1b.

The median modulation indices of Table 2 were tested for significance by the Kruskal–Wallis ranking test (Sachs, 1972). The only significant individual sub-sample result is that for the one-monthly variability (m_1), but again, if we pool the probabilities for the same sub-samples at both frequencies, the median modulation indices for the variable sources in the Galactic centre sector are significantly higher for all the sub-samples.

4 DISCUSSION AND CONCLUSIONS

Consider first the validity of the Culgoora Array data in detail and then discuss the statistical results obtained above.

4.1 The Validity of the Results from SS88

McGilchrist *et al.* (1990) claim, on the basis of their two-epoch observations of six synthesized fields at 151 MHz, that the observations of SS88 are unreliable. They state that the sample of SS88 contains by far too many variable sources, which have unacceptably high modulation indices. We admit to an element of uncertainty in the analysis of SS88 for the following reasons:

(i) The calibration of the flux scale relied on the stability of the calibrators over the interval of 14 years spanned by the SS88 observations. Subsequent analysis showed that some of the calibrators were probably variable at up to the 10 percent level. However, SS88 claim that the effects of such variability on the calibration would have been much reduced by the averaging of conversion factors derived from the several calibrators that were used in each observing session.

(ii) The method of recognizing variability was necessarily a statistical one, based on the dispersion measured in flux density of each of the 412 sources. Since most of the sources (except the calibrators) had only four or five measurements, these individual estimates of the standard deviation were not good estimates of the variance of the population. Each source was assigned a standard deviation equal to the average for a source with that particular flux density. Of course, for any given source, the true standard deviation was equally likely to be above or below the average. Therefore the estimate of χ^2 may have been such as to put the source in the variable class when it was not significantly so and viceversa. In an attempt to reduce the effects of this uncertainty, SS88 recognized two classes of variability, significant at the 95% and 99% confidence levels, respectively. They found that only 27 percent of the sample was variable at the 99% confidence level.

(iii) The measurements of SS88 are not homogeneous with respect to the regularity of their flux density measurements. Many sources were observed two or three times at intervals of two or three months, followed by two or three closely spaced measurements several years later. From this irregularly sampled data, SS88 attempted to deduce variability on both monthly and yearly timescales. It is clear that a regularly sampled series would give one more confidence in the result.

(iv) SS88 could not use a detailed correlation between the variability at 80 MHz and that at 160 MHz to enhance confidence in the result. The 80 MHz and 160 MHz data were taken in different observing sessions, indeed, for some sources, years apart. This may not have been a serious disadvantage for recognizing interstellar scintillation because the drifting diffraction patterns may be highly frequency dependent with the result that little detailed correlation would be expected.

(v) The effects of interplanetary and ionospheric scintillation on SS88 measurements, although potentially significant, were not thought to be important influences. The ratios of the SS88 integration time (11 min) to the interplanetary (1 s) and ionospheric (1 min) timescales were large enough to smooth out these scintillations.

(vi) The fraction of the flux contained in the radio galaxy's core and inner jets (that up to now has been postulated to take part in both intrinsic variability and interstellar scintillation) is usually less than 10% of the total flux density at 5 GHz (Slee *et al.*, 1993). The core fraction will be substantially less at the metre wavelengths. It is therefore hard to accept that such a large proportion of the radio galaxies in SS88 can have modulation indices 10%, unless a large amount of the source's total flux is involved in the variability mechanism. For example, one has to postulate that compact formations are present in the radio galaxy outer part ("hot spots"?) accepted as possible scintillators.

Despite the reservations expressed above, we have retained some confidence in the SS88 results, especially pertaining to variable sources at the 99% confidence level.

Our confidence has been reinforced by computing, from the original Culgoora observations, the averaged "structure functions" (SF) for the variable and non-variable sources tabulated in SS88. The SF (as in the paper of Spangler *et al.*, 1989) was computed for each source with more than 5 observations, using lag intervals of 0.25 year out to a maximum lag of 2.4 year. The SF's show significant differences (especially at 160 MHz) at lags of 0.5, 1.4 and 1.9 year with excess power in the variable group at the first two lags.

Additionally, further synthesis observations of the six fields from McGilchrist *et al.* (1990) have been reported by Riley (1993), this time extending the time interval between observations from one to five years. Despite the fact that these fields are near the anticentre of the Galaxy, mostly at high latitude, Riley finds that up to 40 percent of the flat spectrum sources in this sample show variability over the longer interval.

The above considerations suggest that the results in SS88 cannot be easily rejected. Although caution is needed in accepting the variability of individual sources, the data seems to draw valid statistical conclusions about the dependence of variability on galactic coordinates and on spectral index.

4.2 The Centre - Anticentre LFV Asymmetry as an ISM Influence

It is clear from Tables 1 and 2 that low frequency variable sources are distributed asymmetrically toward the centre and anti-centre of our Galaxy – this is true whether we consider the numbers of sources or their modulation indices. We draw attention to the following features of the statistics:

(i) The asymmetry is stronger for variable sources with $|b| < 30°$.

(ii) The asymmetry is stronger in the numbers of variables sources at 80 than at 160 MHz, but the modulation indices tend to show the opposite effect.

(iii) The numbers of non-variable sources show no asymmetry towards the centre and anti-centre regions.

It is clear from Table 2 that the mean galactic latitudes of the subsamples are not significantly different when their dispersions are taken into account.

It is interesting that, in Table 1b ($|b| < 30°$), the chance probabilities of the centre-anticentre asymmetry for the more probable variable sources (the "99%" subsamples) are systematically lower than those for the less probable variable sources (the "all" subsamples) at both frequencies and both time-scales. Such a regularity does not exist for the "all-sky" variable sources (Table 1a).

That the LFV is stronger at low galactic latitude, especially in the galactic centre region, confirms the weak dependence on galactic latitude found by SS88, who used the same data but did not preform a galactic longitude analysis. The dependence of the LFV on both latitude and longitude gives a strong support for a galactic transmission mechanism, which is likely to be based on scattering by large-scale irregularities in electron density.

It is tempting to interpret these manifestations of the LFV in terms of refractive interstellar scintillations, for which a simple model has been proposed by Rickett (1986). When the intrinsic core diameter of the radio galaxy or quasar is greater than the diameter of the scattering disc due to the interstellar plasma irregularities, then a condition known as "partially quenched scintillation" is believed to occur. Rickett's Figure 1, which summarizes the predictions of his model, shows, for example, that a core at an intermediate galactic latitude with a diameter of 10 mas will have a high and constant scintillation index at frequencies below 160 MHz; the time-scale of the scintillation will vary from 1.5 yr at 160 MHz to 5 yr at 80 MHz.

Some of our results are consistent with this model, for example, the near equality of our median indices at 80 and 160 MHz and the year-to-year variability as measured by SS88's values of m_{12}. However, we also detect significant variability in month-to-month measurements (m_1), which cannot be explained by Rickett's simple model.

Irrespective of the accuracy of the model, the near equality of our measured scintillation indices at 80 and 160 MHz can also be explained by an intrinsic property of the sources; that is, the cores of extragalactic sources have flat radio spectra, while more extended outer jets and lobes have spectra rising steeply towards the low frequencies. Since only the core component will be subject to refractive interstellar scintillation, the modulation index (defined as rms variation/total flux) will tend to decrease towards the lower frequency. The final measured value of the modulation (scintillation) index will depend on a combination of this effect and the model-dependent value of the core scintillation amplitude as a function of frequency.

It is important to emphasize that the method used in this paper of separating the influences of both galactic latitude and longitude is much more efficient than the use of latitude alone. We are at present expanding out analysis of the Culgoora database by using the data on more sources that were not included by SS88. With an expanded analysis, we may be able to demonstrate a more detailed dependence of the LFV on galactic longitude.

If interstellar scintillation is an important contributor to the variability, then one would expect to detect from studies of pulsar scintillation (Alurkar *et al.*, 1986) significant changes in the scintillation index with galactic coordinates (taking the pulsar distance into account).

Acknowledgements

We are indebted to Drs V. Shishov, N. Kardashev, B. Komberg, D. Jauncey and A. Gorshkov for constructive remarks. GT thanks the ATNF staff for the best hospitality during his visit to the ATNF, CSIRO. This study is supported by the Russian Fundamental Research Foundation Grant 93-02-17059.

References

Altschuler, D. R., Broderick, J. J., Condon, J. J., Dennison, B., Mitchell, K. J., O'Dell, S. L. and Payne, H. E. (1984) ***Astron. J.*** **89**, 1784.

Alurkar, S. K., Slee, O. B. and Bobra, A. D. (1986) ***Aust. J. Phys.*** **39**, 433.

Cawthorne, T. V. and Rickett, B. J. (1985) ***Nature*** **315**, 40.

Cordes, J. M., Weisberg, J. W. and Boriakoff, V. (1985) ***Astrophys. J.*** **288**, 221.

Cotton, W. D. and Spangler, S. R. (1979) ***Astrophys. J. Lett.*** **228**, L63.

Fanti, C., Fanti, R., Ficcara, A., Gregorini, L., Mantovani, F. and Padrielli, L. (1981) ***Astron. Astrophys. Suppl.*** **45**, 61.

Fisher, J. R. and Erickson, W. C. (1980) ***Astrophys. J.***, **242**, 884.

Gregorini, L., Ficcara, A. and Padrielli, L. (1986) ***Astron. Astrophys.*** **168**, 25.

Hunstead, R. W. (1972) ***Astrophys. J. Lett.*** **12**, L193.

McAdam, W. B. (1982) *Proc. Workshop on Low Frequency Variability of Extragalactic Radio Sources*, Cotton, W. D. and Spangler, S. R. (eds.), Green Bank, p. 133.
McGilchrist, M. M. and Riley, J. M. (1990) *MNRAS* **246**, 123.
Rao, A. P. and Ananthakrishnan, S. (1984) *Nature* **312**, 707.
Rickett, B. J. (1986) *Astrophys. J.* **307**, 564.
Rickett, B. J., Coles, W. A. and Bourgois, G. (1984) *Astron. Astrophys.* **134**, 390.
Riley, J. M. (1993) *MNRAS* **260**, 893.
Sachs, L. (1972) *Statistische Auswertungsmetoden* (Springer–Verlag, Berlin, New York).
Shapirovskaya, N. (1978) *Sov. Astron.* **22**, 554.
Shapirovskaya, N. and Bocharov, A. (1989) *Astron. Zh.* **63**, 666 (*Sov. Astron.* **30**).
Slee, O. B. (1977) *Austr. J. Phys., Astroph. Suppl.*, 43, 1.
Slee, O. B. and Higgins, C. S. (1975) *Austr. J. Phys., Astroph. Suppl.*, 27, 43.
Slee, O. B. and Siegman, B. S. (1983) *Proc. Astr. Soc. Australia* **5**, 114.
Slee, O. B. and Siegman, B. S. (1988) *MNRAS* **235**, 1313 (SS88).
Slee, O. B., Sadler, E. M., Reynolds, J. E. and Ekers, R. D. (1993) *Submitted to MNRAS.*
Spangler, S. R., Fanti, R., Gregorini, L. and Padrielli, L. (1989) *Astron. Astrophys.* **209**, 315.