HUBBLE SPACE TELESCOPE OBSERVATIONS OF AGN'S IN THE ULTRAVIOLET: BL LAC AND Q2345+007*

JOSEPH F. DOLAN and PATRICIA T. BOYD**
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771

M.J. NELSON, J.W. PERCIVAL and M.J. TAYLOR***
Department of Astronomy and Space Astronomy Laboratory, University of Wisconsin, Madison, WI 53706

G.W. VAN CITTERS
Division of Astronomical Sciences, National Science Foundation, 4201 Wilson Blvd., Arlington, VA 22230

(Received 7 May, 1996; accepted 8 August, 1996)

Abstract. We report the first polarimetric observations in the ultraviolet of two AGN's, the blazar BL Lac and the gravitational lens candidate Q2345+007. We find strong ($p > 3\%$) and variable UV polarization in BL Lac, two of the characteristics exhibited by blazars in the visible. The polarization of BL Lac in the UV decreased significantly (from 18% to $< 5\%$) over a timescale of days. The flux density in the polarimetric bandpass showed changes which were not correlated with the polarimetric changes. The behavior of BL Lac in the UV is consistent with the two-component model of its polarized flux proposed by Brindle *et al.* (1985). The UV properties of the images in the Q2345+007 system are consistent with a gravitational lens interpretation. The QSO imaged in Q2345+007A is an excellent candidate to monitor for variable polarization on a timescale of weeks. Detecting the same polarimetric variation in each image of a gravitational lens may be the most effective method of determining the time-of-flight difference between the two image paths.

1. Introduction

Active galactic nuclei (AGNs) which exhibit, among other characteristics, highly variable luminosity and polarization ($p \geq 3\%$) in the visible region of the spectrum include BL Lacertae objects and optically violently variable (OVV) quasars (cf. Angel and Stockman, 1980 and the references cited therein). The photometric and polarimetric behavior of AGN's is believed to be related to the nature of their energy generation mechanism, and a comparison of the characteristics of BL Lac objects with those of OVV quasars may restrict the class of models which can explain the central energy source in AGNs. The Hubble Space Telescope (HST) now allows us to investigate the properties of AGN's in the UV. Allen *et al.* (1993) and Smith, Allen and Angel (1993) reported strong UV polarization in three BL Lac objects,

* Based in part on observations with the Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by AURA, Inc. under NASA contract NAS 5-26555.
** also Universities Space Research Association.
*** Currently Department of Physics and Engineering, Loras College, P.O. Box 178, Dubuque, IA 52004

Astrophysics and Space Science **240:** 295–303, 1996.

Table I
Photometry of Q2345+007

Date (MJD)	Filter	Bandpass (Å) Obs. Frame	Bandpass (Å) Rest Frame	Flux Density (μJy) A	Flux Density (μJy) B	Photometric Ratio A/B
49289.0	F140LP	1400 – 3000	445 – 950	19 (1)	2.8 (0.2)	6.7 (0.5)
49289.0	F248M	2300 – 2660	730 – 845	17 (4)	5 (3)	3.7 (2.4)
49289.0	F284M	2650 – 3030	840 – 960	38 (4)	7 (2)	5.7 (1.5)
49288.6	F277M	2600 – 2940	825 – 930	48 (2)	5.8 (1.0)	8.3 (1.4)
49303.6	F277M	”	”	43 (2)	6.8 (1.4)	6.3 (1.3)
49312.5	F277M	”	”	48 (2)	12 (2)	4.0 (1.5)

and Dolan *et al.* (1994) reported strong UV polarization in the OVV quasar 3C345. None of these studies established the polarimetric variability of these AGN's in the UV, however. We report here HST observations of BL Lac, the prototype of its class, and Q2345+007, a known variable quasar (Sol *et al.*, 1984) and gravitational lens candidate. We find that BL Lac exhibits variable luminosity and polarization in the UV, and Q2345+007 exhibits variable luminosity and is an excellent candidate to observe for variable polarization.

BL Lac lies at the center of a giant elliptical galaxy with $z = 0.069$ (Miller, French and Hawley, 1978; Vermeulen *et al.*, 1995). Its polarization in the visible has varied between 2% and 23% since its discovery, with no preferred position angle predominating for any extended interval of time (Angel and Stockman, 1980; Mead *et al.*, 1990). Although BL Lac is at galactic latitude $b = -10°$, Angel and Stockman (1980) infer from the nature of its polarimetric variability that it does not contain a significant component of interstellar polarization.

Q2345+007, discovered by Weedman *et al.* (1982), is a pair of quasars, denoted A and B, which are separated by 7.3″. Based on their similar redshifts and spectra, Weedman *et al.* identified the pair as a gravitational lens. Sol *et al.* (1984) report $\sim$ 0.2 mag variability in both components of Q2345+007 over a time scale of months. OVV quasars exhibit photometric and polarimetric variability on a timescale of days, together with a steep optical spectrum and a compact, flat spectrum counterpart in the radio (Bregman *et al.*, 1986). Although more philately than physics at this level of classification, Q2345+007 is technically not an OVV quasar because its radio counterpart has not yet been detected (Sol *et al.*, 1984). Nevertheless, if Q2345+007 has the optical characteristics of an OVV quasar, then it should exhibit photometric variability on a timescale of days, together with strong and variable polarization (Angel and Stockman, 1980).

The HSP observations we report here are the first measurements of the UV polarization of both sources.

2. Observations

All observations were obtained with the High Speed Photometer (HSP), one of the first-generation instruments on board the HST. A description of the HSP and its method of operation is given in Bless *et al.* (1996). The FWHM response of the filters we used, assuming a flat incident spectrum, is given in Table I (Bless *et al.*, 1992). Photometric and polarimetric bandpasses are defined in the observer's rest frame; their extent in the rest frame of Q2345+007 is also given in Table I. The FWHM of the F277M bandpass in the rest frame of BL Lac was 2430 – 2750 Å. Interleaved background observations were taken during the observations at locations 11″ and 15″ away from each target along a direction not near the position angle of any other known source. Flux densities in the individual bandpasses were calibrated by observations of BD + 75° 325 (Bless *et al.*, 1996), an 05p IUE spectrophotometric standard.

Polarimetric observations were obtained in the F277M bandpass using a 0.65″ diameter aperture. Successive measurements were obtained of the count rates in each of four analyzers oriented at 45° intervals. The measurements were combined into a single set of count rates using the method recommended by Clarke *et al.* (1983). The normalized Stokes parameters and their associated uncertainties were then derived by the procedure outlined by Dolan *et al.* (1994). To derive the flux density in the F277M bandpass, we used the average of the summed count rates in the $0° + 90°$ orientation analyzers and the summed count rates in the $45° + 135°$ pair (Dolan *et al.*, 1994).

We observed the two image components of Q2345+007 photometrically in three UV passbands, F140LP, F248M, and F284M, on 1993 October 28 using a 1″ diameter aperture. The photometric ratio of Q2345+007 A to B in any bandpass (i.e., the ratio of the flux density in image A to that in image B), which is the quantity of interest in verifying the gravitational lens interpretation of the system, is independent of the conversion from observed count rate to flux density. Hence, the photometric ratios we report are the ratios of the observed count rates after subtraction of background and dark count. Observations of Q2345+007 in the F277M polarimetric bandpass were obtained on 1993 October 28, November 12, and November 21.

BL Lac was observed in the F277M polarimetric bandpass on five separate epochs between 1993 October 4 and 11. The observations were spaced at approximately two day intervals.

3. Results

3.1. BL Lacertae

The UV polarization of BL Lacertae over the eight days we monitored it is shown in Figure 1. The maximum polarization we measured was $p = 18 \pm 3\%$, at the

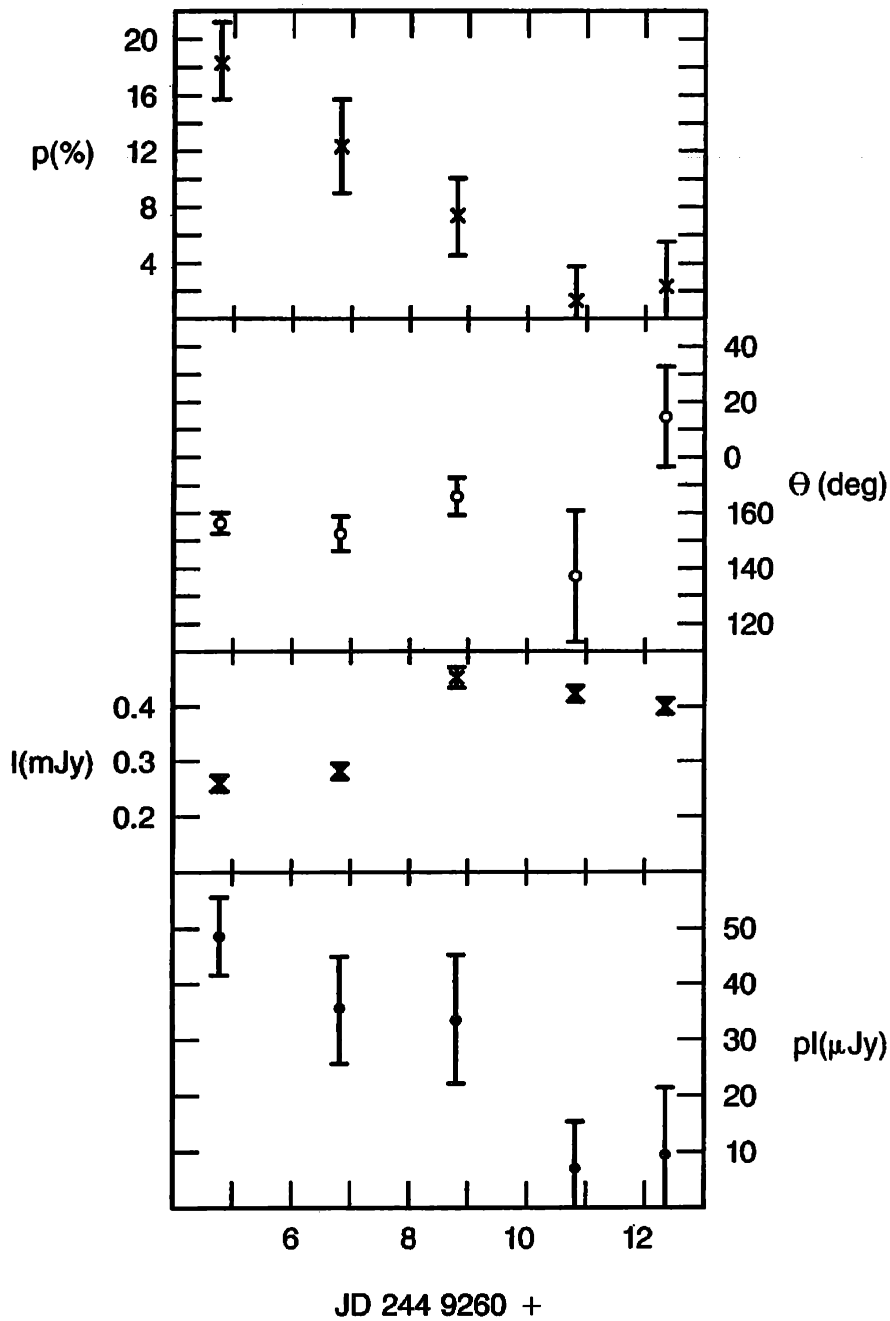

Figure 1. The 2770 Å polarization of BL Lac between 1993 October 4 and 11. From top to bottom are the polarization; its position angle in the equatorial co-ordinate system; the flux density in the F277M bandpass; and the polarized flux density. The vertical bars are $\pm 1\sigma$ uncertainties on each measurement.

start of the observations. The percentage polarization in Figure 1 was corrected for its non-normal distribution at low statistical significance (Simmons and Stewart, 1985) using the correction factor of Wardle and Kronberg (1974),

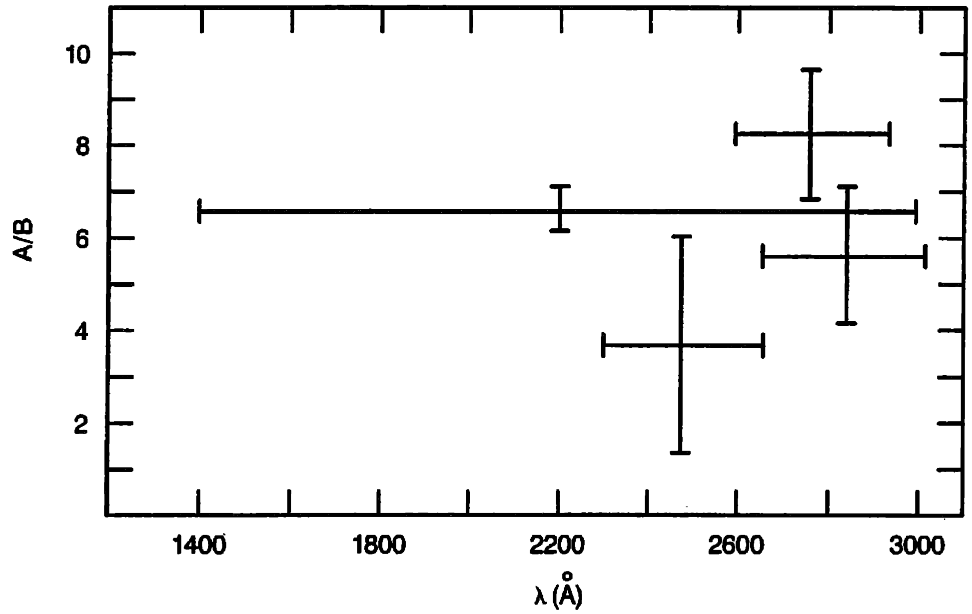

Figure 2. The photometric ratio of the flux density of Q2345+007A to B observed on 1993 October 28 in four UV bandpasses. The horizontal bars demarcate the FWHM of the bandpass in the observer's frame; see Table I for their extent in the rest frame of the quasar. The $\pm 1\sigma$ uncertainty in the photometric ratio is shown as a vertical line.

$$p = p_0[1 - (\sigma/p_0)^2]^{1/2}, \tag{1}$$

where p_0 is the observed value of the polarization and σ is its associated standard deviation. The null hypothesis of constant Stokes parameter $q(u)$ about its weighted mean gives $\chi^2 = 13$ (17) for four degrees of freedom, a value exceeded by only 1.0% (0.2%) of all random distributions having the same mean and variance as our data set. The joint probability of both data sets being non-varying is 0.02%. The UV polarization of BL Lac must vary significantly over a timescale of days.

The polarization we observe declines monotonically with time, dropping below 5% after six days. The associated position angle is essentially constant for most of the decline in polarization, and then shows no preferred direction. This behavior of p and θ is typical of that displayed by BL Lac in the visible (Mead *et al.*, 1990). The flux density, I, in the F277M bandpass is also shown in Figure 1, together with the polarized flux density, pI. Neither data set is consistent with a constant value over eight days ($\chi^2 = 26$ and 15.4, respectively). Although pI decreases with decreasing polarization, the correlation is produced entirely by p, not by I. The UV flux density does not correlate with the UV polarization. At first I is almost constant, then greatly increases, and finally decreases while p monotonically decreases.

Table II
Polarimetry of Q2345+007A

Date (MJD)	p	θ (deg)
49288.4	0.00 ± 0.05	131 ± 45
49303.4	0.14 0.07	86 11
49312.3	0.00 0.06	173 45

3.2. Q2345+007

The flux densities we observed from the two components of Q2345+007 are given in Table I, together with the photometric ratio of A to B in each bandpass. No attempt was made to correct the UV flux densities for galactic reddening, which is negligible in the direction of Q2345+007 ($1 = 91°$, $b = -60°$). The photometric ratios we observed in the four UV bandpasses on 1993 October 28 (Figure 2) are consistent under the assumptions of the χ^2 test with a single value independent of frequency, $A/B = 6.7 \pm 0.5$ ($\chi^2 = 3.3$ for three degrees of freedom). The photometric ratio in the F277M bandpass decreases between October 28 and November 21. The decrease is caused by a brightening of component B on November 21.

Our polarimetric observations of Q2345+007A are summarized in Table II. The second column gives the corrected polarization (see Equation 1) and its associated one standard deviation uncertainty. The position angle of the polarization in the equatorial co-ordinate system is listed in the third column. Because component B was $1.5 - 2.3$ mag fainter than A in the F277M bandpass, we could only place a 1σ upper limit on its polarization at every epoch, $p \leq 0.2$.

The Stokes parameters q' and u' we observed from Q2345+007A in the internal co-ordinate system of the polarimeter are shown in Figure 3. Positive q' was oriented at position angle 204°.0 on the sky. The vector polarization in Figure 3 observed on 1993 November 12 is different from zero at the 98% level of confidence. Both large UV polarization and variable UV polarization on a timescale of days are indicated in Q2345+007, but at a significance below the 99% level of confidence. Q2345+007 is an excellent candidate to monitor for large and variable polarization, both in the UV and in the visible.

4. Discussion

4.1. UV Polarization of BL Lac

The lack of correlation between changes in UV luminosity and polarization in BL Lac, the timescale of these changes (a few days), and the constancy of the position angle during some polarimetric variations and its lack of a preferred direction

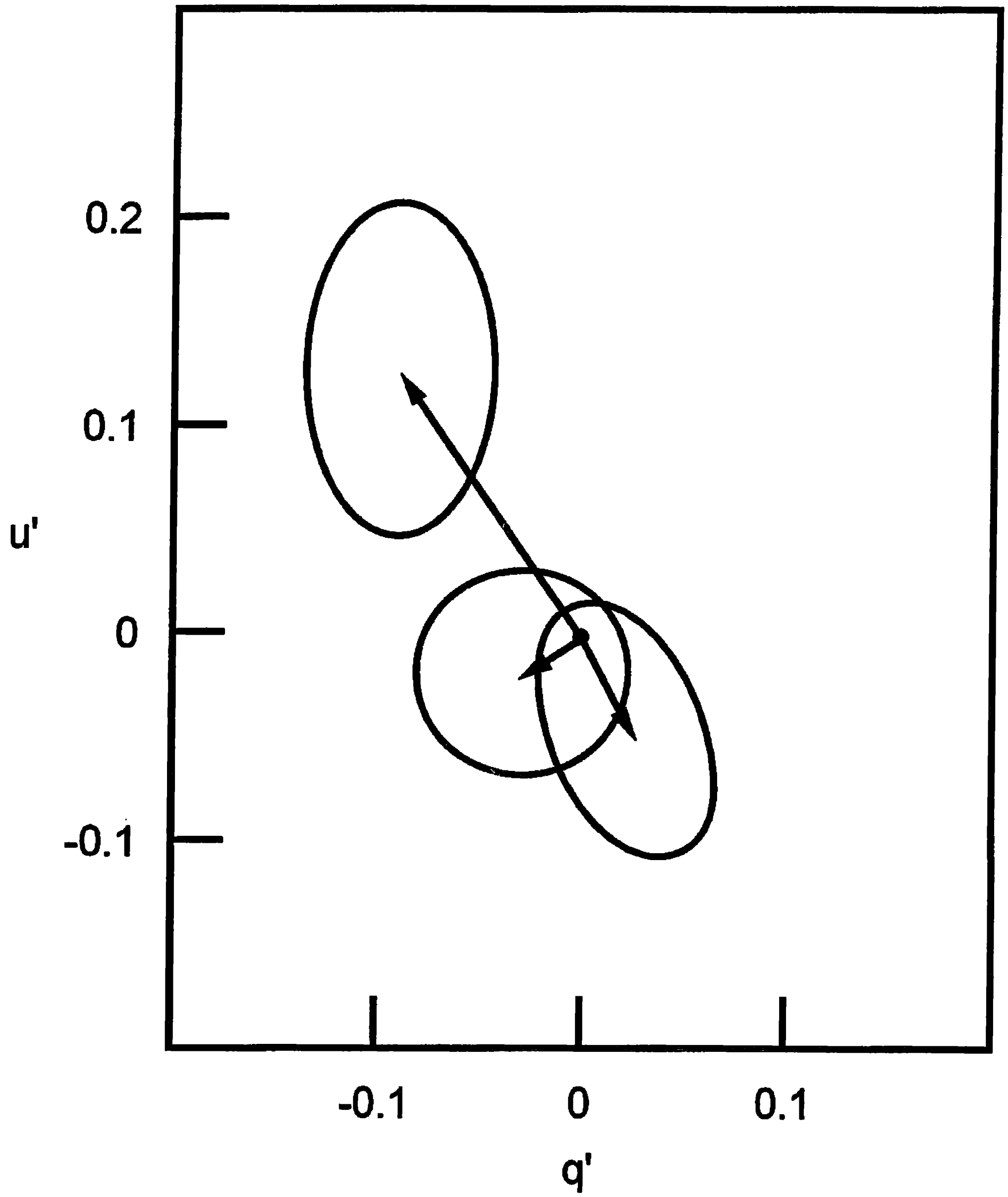

Figure 3. The UV polarizations observed from Q2345+007A in the space of the internal Stokes parameters, q' and u'. The length of the vector is p, and the position angle of the vector measured ccw from the $+q'$ axis is $2(\theta - 204°)$. The origin of each vector is the null polarization point. The $\pm 1\sigma$ uncertainty on q' and u' are the axes of the error ellipse associated with the vertex of **p**.

during others, is identical to the behavior of this blazar in the visible (Moore *et al.*, 1982; Brindle *et al.*, 1985; Mead *et al.*, 1990). Brindle *et al.* (1985) reproduced this characteristic behavior in the visible using a model consisting of two polarized components, one having variable p, θ and I, and the other having fixed p (= 20%), θ (= 30°), and I. They identify the fixed component as being associated with the inner region of the optical jet in BL Lac. Because the polarimetric behavior we observe in the UV from BL Lac is the same as that observed in the visible, our observations are also consistent with the two-component model of Brindle *et al.*

4.2. Q2345+007

All our observations of Q2345+007 in the UV are consistent with it being a gravitationally lensed quasar. The Stokes parameters q and u of gravitationally lensed images will be unchanged from those of the source if both source and observer are at large distances from the deflecting mass and the deflecting mass is neither rapidly rotating nor strongly charged (Mashoon, 1973, 1974). The image of a lensed quasar at time t will exhibit the polarization of the quasar at time $t - \tau$, where τ is the time-of-flight of light along the ray path from the quasar to the Earth. If the polarization of the lensed quasar changes with time, then different images may possess different polarizations at a single epoch in the observer's frame. Observing the same polarimetric variation at two different times in the two images may provide the best method of determining the time-of-flight differences between the image paths. This path-length difference can be related to the linear distance between the paths at the deflector, from which one can estimate the Hubble constant (Refsdal, 1964; Shapiro, 1986; but cf. Alcock and Anderson, 1985; Watanabe *et al.*, 1992). Previous attempts to monitor lensed images in both the radio and optical regions of the spectrum have concentrated on the detection of the same photometric variation to determine a path-length difference (Lehar *et al.*, 1992; Press *et al.*, 1992a, 1992b; Schild, 1990; Vanderriest *et al.*, 1989). Because polarimetric variability involves two Stokes parameters (q and u) instead of one (I), polarimetric variability is plotted onto a plane rather than a line (cf. Phinney, 1985). A polarimetric variation should be easier to correlate in the separate images than a photometric one.

If the lensed quasar in Q2345+007 is a polarimetric variable, as our UV observations indicate, then polarimetric monitoring, even in the visible, may be the most effective method of determining time-of-flight differences between the image paths in this system. Observers should consider monitoring gravitational lens systems polarimetrically as well as photometrically for this reason.

Acknowledgements

We thank an anonymous referee for suggestions improving the presentation of the paper. The High Speed Photometer Investigation Definition Team is supported by NASA contract NAG 5-1613 to the University of Wisconsi. PTB acknowledges support from NASA contract NAS 5-32484 to USRA.

References

Alcock, C. and Anderson, N.: 1985, *Astrophys. J.* **291**, L29.

Allen, R.G., Smith, P.S., Angel, J.R.P., Miller, B.W., Anderson, S.F. and Margon, B.: 1993, *Astrophys. J.* **403**, 610.
Angel, J.R.P. and Stockman, H.S.: 1980, *Ann. Rev. Astron. Astrophys.* **18**, 321.
Bless, R.C., Percival, J.W., Walter, L.E. and White, R.L.: 1992, *High-Speed Photometer Instrument Handbook*, STScI: Baltimore.
Bless, R.C., *et al.*: 1996, in preparation.
Bregman, J.N., *et al.*: 1986, *Astrophys. J.* **301**, 708.
Brindle, C., *et al.*: 1985, *Mon. Not. R. Astron. Soc.* **214**, 619.
Clarke, D., Stewart, B.G., Schwarz, H.E. and Brooks, A.: 1983, *Astron. Astrophys.* **126**, 260.
Dolan, J.F., *et al.*: 1994, *Astrophys. J.* **432**, 560.
Lehar, J., Hewitt, J.N., Roberts, D.H. and Burke, B.F.: 1992, *Astrophys. J.* **384**, 453.
Mashoon, B.: 1974, *Phys. Rev.* **D10**, 1059.
Mashoon, B.: 1973, *Phys. Rev.* **D7**, 2807.
Mead, A.R.G., Ballard, K.R., Brand, P.W.J.L., Hough, J.H., Brindle, C. and Bailey, J.A.: 1990, *Astron. Astrophys. Suppl. Ser.* **83**, 183.
Miller, J.S., French, H.B. and Hawley, S.A.: 1978, *Astrophys. J.* **219**, L85.
Moore, R.L., *et al.*: 1982, *Astrophys. J.* **260**, 415.
Phinney, E.S.: 1985, in: J.S. Miller (ed.), *Astrophysics of Active Galaxies and Quasi-Stellar Objects*, University Science Books: Mill Valley, CA, 453.
Press, W.H., Rybicki, G.B. and Hewitt, J.N.: 1992a, *Astrophys. J.* **385**, 404.
Press, W.H., Rybicki, G.B. and Hewitt, J.N.: 1992b, *Astrophys. J.* **385**, 416.
Refsdal, S.: 1964, *Mon. Not. R. Astron. Soc.* **128**, 307.
Shapiro, I.: 1986, *Nature* **324**, 10.
Schild, R.E.: 1990, *Astron. J.* **100**, 1771.
Simmons, J.F.L. and Stewart, B.G.: 1985, *Astron. Astrophys.* **142**, 100.
Smith, P.S., Allen, R.G. and Angel, J.R.P.: 1993, *Astrophys. J.* **415**, L83.
Sol, H., Vanderriest, C., Lelievre, G., Pedersen, H. and Schneider, J.: 1984, *Astron. Astrophys.* **132**, 105.
Vanderriest, C., Schneider, J., Herpe, G., Chevreton, M., Moles, M. and Wlerick, G.: 1989, *Astron. Astrophys.* **215**, 1.
Vermeulen, R.C., Browne, I.W.A., Cohen, M.H., Goodrich, R.W., Ogle, P.M., Readhead, A.C.S. and Tran, H.D.: 1995, *IAU Circ.*, 6176.
Wardle, J.F.C. and Kronberg, P.P.: 1974, *Astrophys. J.* **194**, 249.
Watanabe, K., Sasaki, M. and Tomita, K.: 1992, *Astrophys. J.* **394**, 38.
Weedman, D.W., Weymann, R.J., Green, R.F. and Heckman, T.M.: 1982, *Astrophys. J.* **255**, L5.