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RAPID VARIABILITY OF QUASARS

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Abstract

Observations with the Effelsberg 100-m telescope and the Very Large Array (VLA) have shown that the radio emission of some quasars and BL Lacertae objects varies on the time scale of only one day. Simultaneous optical variations have been detected with a 71-cm telescope of the Landessternwarte Heidelberg and the Calar Alto 2.2-m telescope. These observations pose serious problems to the generally accepted "standard model" of quasars; it has not yet been possible to explain them completely. More observations to characterize the properties of rapid variability in quasars are urgently needed. Regular monitoring of a few relatively bright objects might be a challenging but rewarding project for observers with telescopes of moderate size and CCD equipment.

1. Introduction

On photographic plates, quasars appear to be stellar objects, but examination of their spectra reveals that they have very large redshifts (roughly in the range from 0.1 to 4). It is generally accepted now that the origin of these redshifts (as for the redshifts of galaxies) is the expansion of the universe. Because of Hubble's law, quasars therefore are among the most distant and most luminous objects we can observe.

Most quasars are variable, and much of our knowledge about these exotic objects is actually based on the analysis of their variations. Most fundamentally, variability allows us to place upper limits on the size of the active regions in celestial objects. The basic argument is simple: Since no signal can travel faster than the speed of light, an object of size L cannot vary on time scales much shorter than $t = L/c$, the time needed for the information "that something is going on" to reach the edges of the object. (Since we are interested in order-of-magnitude estimates, factors of order unity are neglected here.) Information about the physical conditions and processes in quasars can be inferred from more detailed studies of their variations across the electromagnetic spectrum; simultaneous multi-wavelength observations are particularly useful.

In this article, I will briefly summarize some features of the "standard model" for quasars which are directly related to variability; then I will describe recent observations of rapid variations, which present a considerable challenge to our current understanding of these objects. Finally, I will try to point out some directions for future research, with emphasis on studies that can be carried out with CCDs on telescopes of moderate size.

In the following sections, the term "quasar" will be used somewhat loosely as a generic term, without distinction between "proper" quasars and, e.g., BL Lacertae objects, unless otherwise noted. Radio-quiet quasars are not considered, however.

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2. The "Standard Model" of Radio Quasars

From the spectral shape of the radio continuum, it was concluded in the 1960's that the mechanism responsible for this emission is non-thermal synchrotron radiation. It is produced by highly relativistic electrons gyrating in a magnetic field. Early variability studies showed that many quasars are variable on the time scale of a month; the light travel time argument thus gives a maximum source size of 0.1 pc. Combining this value with typical distances and flux densities gives a brightness temperature of 10^{15}K. (The brightness temperature is not a physical temperature, but rather a measure of surface brightness. It is the temperature a hypothetical thermal emitter would have to have in order to produce the observed radio emission.) Enormously high brightness temperatures are inconsistent with theoretical considerations, however. The relativistic electrons collide with their own synchrotron photons and scatter them into the X-ray regime (inverse Compton scattering). The energy loss in these collisions is extremely large, and the brightness temperature should decrease to 10^{12}K within seconds; this is the so-called "inverse Compton catastrophe".

This discrepancy can be circumvented by postulating that the radio emission region moves towards the observer at a speed that is close to the speed of light, so that relativistic effects have to be taken into account. First, the Doppler effect leads to an underestimate of the real time scale of the variability. (An object approaching the observer behaves like a 33-rpm record accidentally played at 78 rpm; not only is the pitch too high, but also the music plays too fast!) Second, the radiation of an emitter moving at relativistic speed is not isotropic, but rather beamed in the direction of the motion. If this effect is ignored, the total luminosity of objects approaching the observer is strongly overestimated. A quantitative treatment shows that the brightness temperature of quasars can be reduced from 10^{15}K to the inverse Compton limit of 10^{12}K by assuming that the emitting material moves towards the observer with a Lorentz factor of order 10, i.e., with about 99.5% of the speed of light. This prediction of "bulk relativistic motion", based on variability studies, has been confirmed impressively by Very Long Baseline Interferometry (VLBI). Images with milliarcsecond resolution obtained with this technique in intervals of a few years reveal directly the outward motion in the radio jets associated with quasars. The detailed mechanism for the formation and acceleration of these jets has remained elusive, however.

In analogy with stellar systems (e.g., cataclysmic variables, T Tauri stars), it is generally assumed that quasars are powered by infalling gas, which forms a disk around the massive object at the core of the quasar. While the matter ejected from the central engine can be traced directly in radio images, information about the accreting material feeding the "monster" is far more indirect. The thermal emission of the accretion disk peaks in the extreme ultraviolet and is therefore very difficult to observe. (The interstellar medium is highly opaque between the Lyman limit and the X-ray regime.) The continuum emission in the optical and near ultraviolet spectral regions can be studied, however, and again variability contains the largest amount of information. Unfortunately, it is very difficult in many cases to determine the relative contributions to the optical continuum from the disk and the jet. In this context, it should be pointed out that a dubious use of the light travel time argument is frequently found in the literature. If optical variations with a time scale t are observed, it is concluded that the emission comes from a region close to the nucleus, at most L = ct away. This estimate is then used to set an upper limit on the mass of the putative black hole at the center, on the basis that the Schwarzschild radius must be smaller than about L/3. The flaw in this argument is the fact that the light travel time

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argument gives an estimate for the size of the variable region, but not necessarily for its distance from the nucleus. The observed fluctuations could therefore be due to localized flare-like events somewhere on the accretion disk or even to shocks in the jet, far away from the central engine. The observations of 0716+714 described below actually make a point in favor of the latter interpretation.

3. Observations of Rapid Variability in Quasars

Beginning in 1985, we (i.e., a group lead by A. Witzel at the Max-Planck-Institute in Bonn) performed a series of observations with the 100-m radio telescope in Effelsberg to search for variability of quasars at wavelengths of 6 and 11 cm. We selected a sample of circumpolar (declination > 60°) flat-spectrum sources, which could be monitored around the clock. Almost half of the observing time was spent on non-variable comparison sources; the very careful calibration resulted in a final accuracy of 0.3% for relative flux densities. (The absolute scale is only good to a few per cent.) Figure 1 shows the radio "light curve" of 0917+624 obtained in a five-day observing run (Quirrenbach *et al.* 1989). Relatively large variations with a peak-to-peak amplitude of more than 20% and a typical time scale on the order of one day are immediately apparent, but there is also fast (about one hour) variability of a few per cent.

In subsequent observing periods, the characteristics of intraday radio variability were studied in more detail. It was found that in 0917+624 the variations of the total flux density are accompanied by even more dramatic changes of the polarization. Simultaneous observations with the 100-m telescope and the Very Large Array (VLA) were conducted to investigate the spectral properties of the variations. As can be seen from Figure 2, the variations are well-correlated at wavelengths from 2 to 11 cm, with larger amplitudes at longer wavelengths. At 20 cm, the "light curve" looks quite different, and the amplitude is somewhat lower again.

Optical observations of six radio-variable sources were carried out with a CCD camera attached to a 71-cm telescope of the Landessternwarte on Koenigstuhl, Heidelberg. Integration times ranged from 10 to 30 minutes; a Johnson R filter was used. The CCD frames were corrected for dark and bias, and flat-fielded using twilight frames. They were also corrected for fringing. Within each of the 5.2-by-7.8-arcminute fields, about 10 to 15 stars within 2 magnitudes of the brightness of the corresponding quasar were detected. On each frame, relative photometry between the quasar and these stars was carried out; variable stars were identified and excluded from the analysis.

In the first observing run, surprisingly large and rapid variations in 0716+714 and 0954+658, and a possible link between optical and radio variations were found (Wagner *et al.* 1990). Therefore, a larger campaign was organized in February 1990; simultaneous observations spanning four weeks were carried out with the 71-cm Koenigstuhl telescope, the 2.2-m telescope on Calar Alto, Spain, and four antennas of the VLA. Figure 3 shows the light curve in the Johnson R band of 0954+658 from the combined data obtained with the 71-cm and 2.2-m telescopes. Several very strong and rapid outbursts are observed. The brightness of 0954+658 changes by a factor of six within a few days; the e-folding times of the outbursts are as short as 6.4 hours (Wagner *et al.* 1993).

One night of data on 0716+714 is shown in Figure 4; different symbols were used for the data from Koenigstuhl and Calar Alto. The agreement between the two data sets is excellent; this demonstrates the high quality of the data from a relatively small instrument (see also Wagner 1990). The full four-week light curve of 0716+714 in the R-band and at 6 cm is shown in Figure 5. The variations at the two widely different wavelengths appear to be correlated. Whereas fast variations are observed in the

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optical and radio during the first few days, there is a simultaneous transition around J.D. 2447930 to a somewhat lower flux level and a slower mode of variations (Quirrenbach *et al.* 1991). This parallel behavior provides very strong evidence for a physical connection between the optical and radio variations.

4. Consequences of Rapid Variability for our Understanding of Quasars

From the discussion in Section 2, it is immediately clear that rapid radio variations make the inverse Compton problem even worse; apparent brightness temperatures as high as 10^{19}K are implied. To reconcile this value with the 10^{12}K limit, it is obviously possible to postulate that typical Lorentz factors for the bulk relativstic motions are of order 200, not 10 as previously assumed, corresponding to an increase from 99.5% to 99.999% of the speed of light. This possibility does not seem very likely, however, since Lorentz factors of about 10 are supported by independent evidence from VLBI images and X-ray observations. Furthermore, a 20-fold increase of the postulated Lorentz factor means that the kinetic energy in the jet must be 20 times higher, further aggravating the puzzle of the acceleration mechanism.

A promising alternative class of models is based on the idea that the variability might be due to shocks in the jet interacting with pre-existing inhomogeneities. In a suitable geometric configuration, a large region might be illuminated almost instantaneously, so that the light travel time argument does not hold. While in these models the 10^{12}K intrinsic brightness limit is observed, it has also been suggested that we might observe "exotic" emission processes, for which this limit does not apply. Examples of such processes would be coherent plasma emission or synchrotron emission from an anisotropic particle population. These attempts to explain rapid variability all include major modifications to the "standard model" of quasars.

Because of the difficulties in explaining rapid radio variability within the framework of the "standard model", a radically different interpretation has also been put forward. In this approach, the variations are not intrinsic to the quasar, but rather are a propagation phenomenon. It is well known that the ionized component of the interstellar medium (ISM) has effects on radio waves that are quite similar to the scintillation of starlight in the earth's atmosphere. Many aspects of the observed variations can actually be reproduced by models of refractive interstellar scintillation (RISS), although somewhat non-standard parameters for the ISM might be needed. Whereas RISS might be responsible for the variability in some sources, it cannot explain the correlation between radio and optical variations in 0716+714, since visible light is not affected by the ionized ISM. At least in this source, intrinsic variations seem to be dominant, and shock models appear to hold the greatest promise to explain the details of the observations. As pointed out in Section 2, as an important consequence of this scenario, the variable optical emission would come from the jets, not from the accretion disks.

5. Some Possible Future Directions

From the discussion in Section 4, it is clear that the investigation of rapid variability in quasars has just begun. Data are available on only a few objects, and little is known about correlations between different wavelength bands. The problem is further compounded by the fact that the statistical properties of the variations in a given source can change from one week to the next (as in 0716+714). It is clear that long-term monitoring programs are required to collect the amount of data necessary to establish a reliable statistical basis for theoretical interpretations. Because of the massive amount of telescope time required, and the heavy oversubscription of all large instruments, telescopes of moderate size can make an extremely useful contribution to this effort.

By the standards of amateur astronomers, even the brightest quasars are faint objects, but the advent of relatively cheap CCDs has greatly expanded the reach of our telescopes. Relative photometry has become relatively easy to do, since there are usually several suitable comparison stars in the field of view. The great enthusiasm for this emerging area by amateurs and college astronomy departments is evidenced by the interest generated by the recent CCD workshops co-sponsored by the AAVSO and AAS (see the proceedings in this volume). The basic requirement for successful quasar observations is the ability to do relative photometry at the 10% (0.1 mag) level for, say, 15th magnitude objects. Since the light curves may be very erratic, but the variability amplitudes are frequently very large, frequent sampling is much more important than superb precision.

Although in the long term statistical information on a large number of quasars will be needed, observational efforts should be concentrated on very few sources initially. A single well-sampled light curve will tell us much more than scattered data points on a wide variety of objects. At this time, it is very difficult to make definite recommendations about the "most rewarding" targets for an observing program. My personal "best bet", however, is 0716+714, for a number of reasons. This source (a BL Lac object) is one of the brightest quasar-like objects in the sky. It is known to be strongly and rapidly variable not only in the visual, but also in the radio, mm, ultraviolet, X-ray and even gamma-ray regimes; there seems to be little dilution of the variable non-thermal radiation by thermal emission. Because of the high declination, light curves without seasonal gaps can be obtained. These properties make 0716+714 particularly suited for a detailed investigation of variability on all time scales. A finder chart for 0716+714 is given in Figure 6.

Those who might consider starting serious quasar observations will probably need more information than can be provided in this article. A summary of rapid variability in the radio regime is given by Quirrenbach *et al.* (1992). More general information about quasars can be found in the catalogs by Kuehr *et al.* (1981) and by Veron-Cetty and Veron (1989). The conference proceedings edited by Zensus and Pearson (1990) and by Duschl and Wagner (1992) provide an excellent review of our current understanding of quasars and related objects. Although the articles in these books provide for some interesting reading, nothing beats going out to the telescope to collect original, scientifically valuable data. I hope that I have been able to show that quasars provide an excellent opportunity for doing just that.

6. Acknowledgements

I am grateful to my collaborators on quasar variability, especially A. Witzel and S. Wagner; the results presented in this article could not have been obtained without them. I would also like to thank the Alexander von Humboldt Foundation for their financial support through a Feodor Lynen fellowship.

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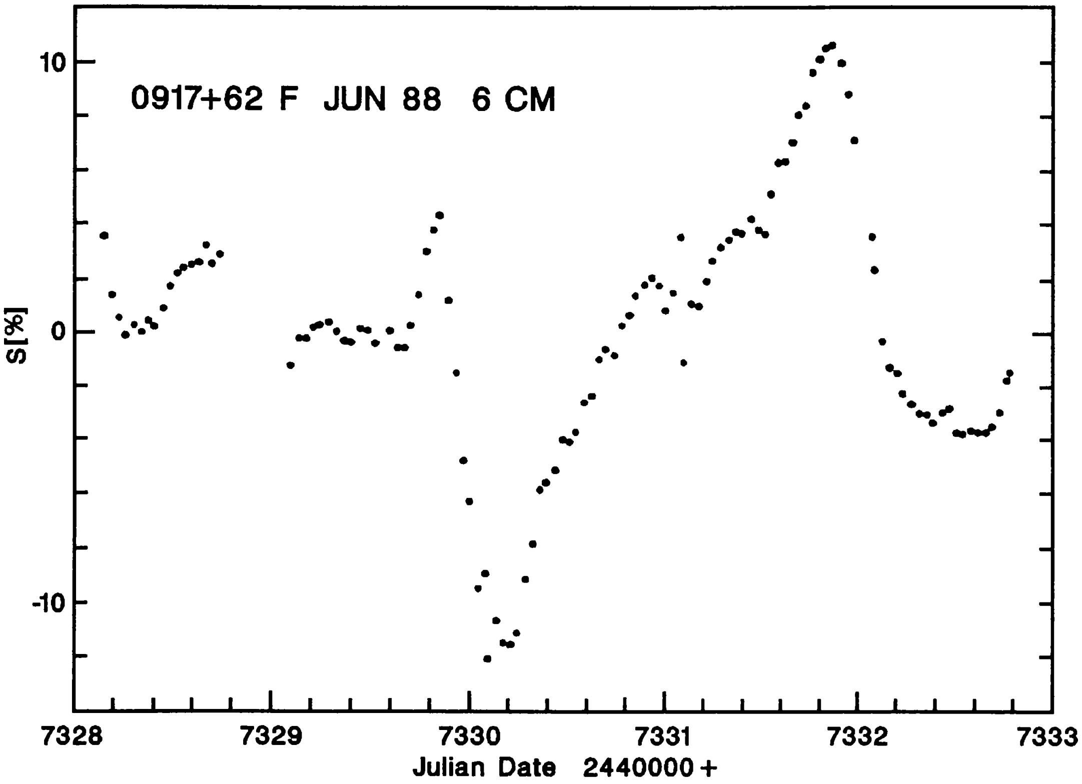

Figure 1. "Light curve" of the quasar 0917+624 at 6 cm wavelength, obtained with the Effelsberg 100 m radio telescope in June 1988. The y-axis gives the residual from the average flux density in per cent.

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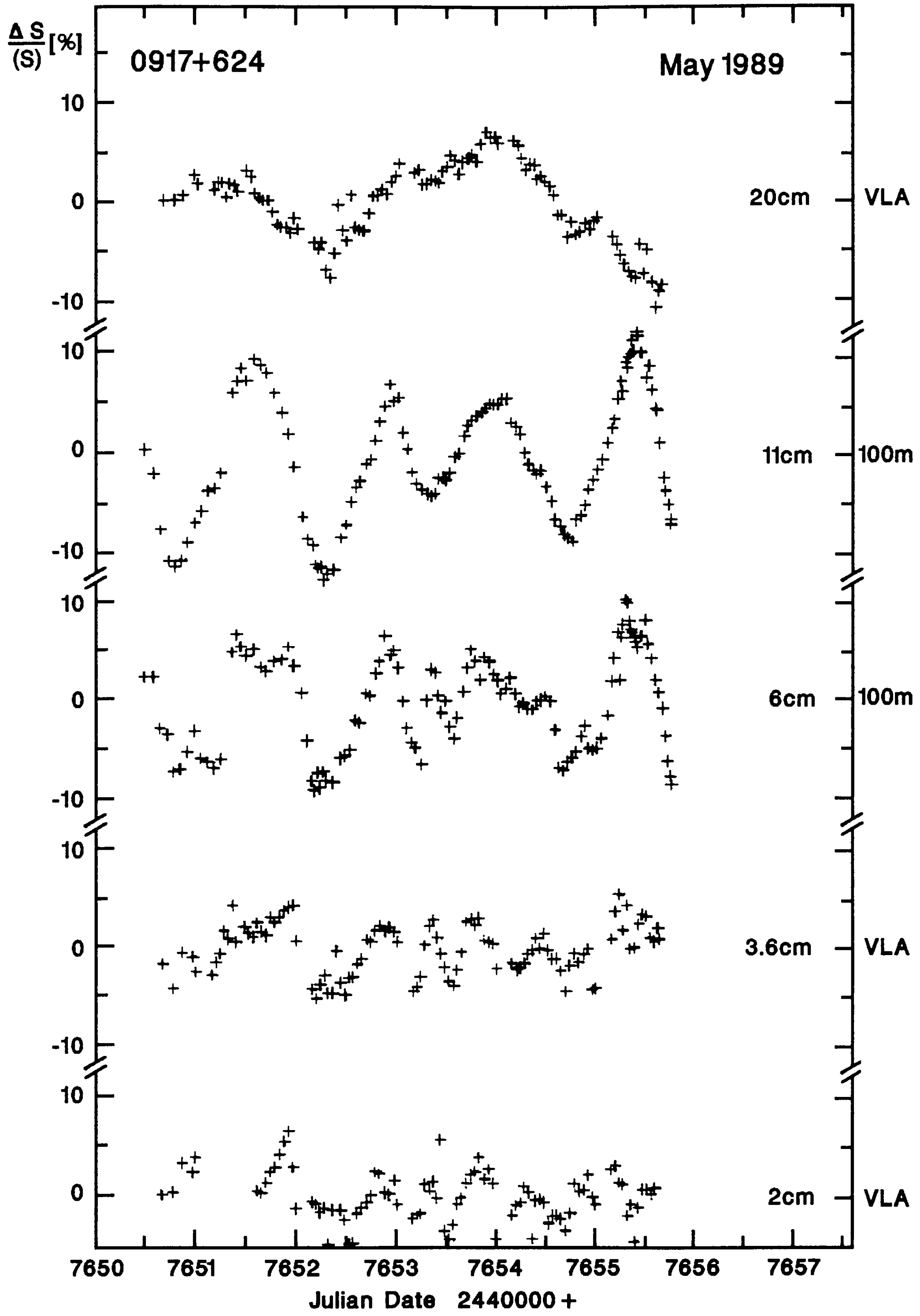

Figure 2. "Light curves" of the quasar 0917+624 at five wavelengths, obtained simultaneously with the Effelsberg 100 m telescope and the VLA in May 1989. The y-axis is as in Figure 1.

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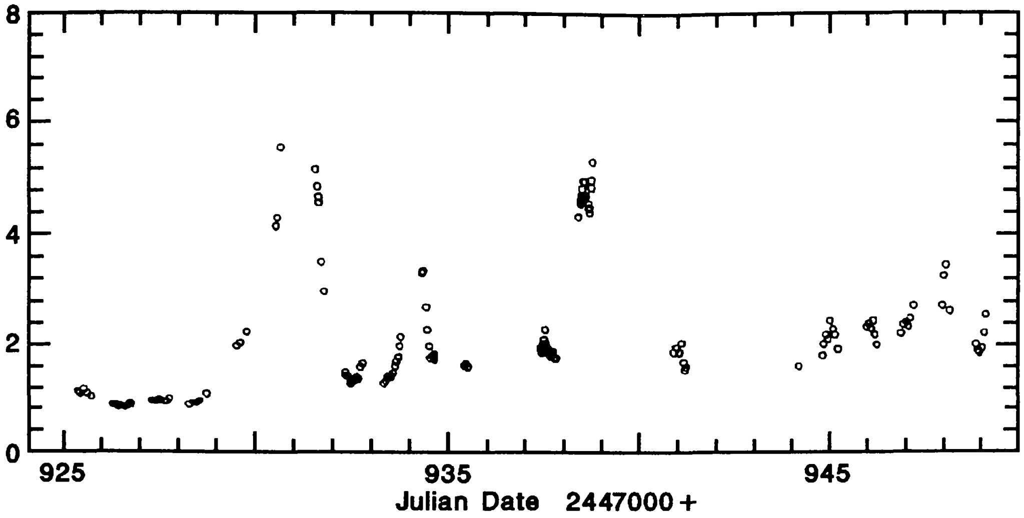

Figure 3. Light curve of the BL Lacertae object 0954+658 in the optical (R band). The y-axis gives brightness in arbitrary units, on a linear scale.

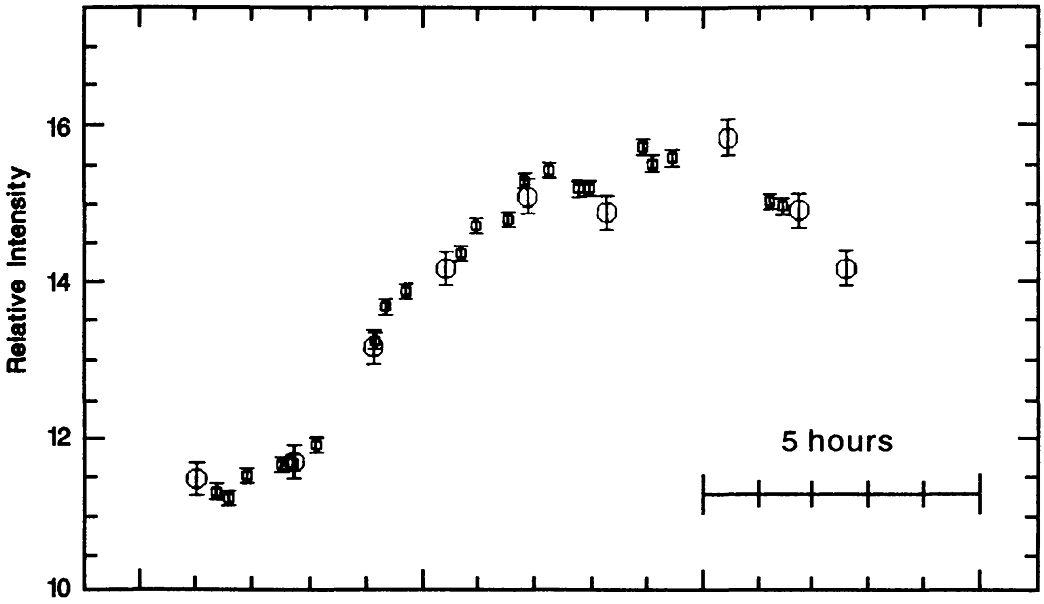

Figure 4. Light curve of the BL Lacertae object 0716+714 in the optical (R band). The y-axis is as in Figure 3. The small symbols are data from the 2.2 m telescope on Calar Alto; the large symbols are from the 71 cm telescope on Koenigstuhl, Heidelberg.

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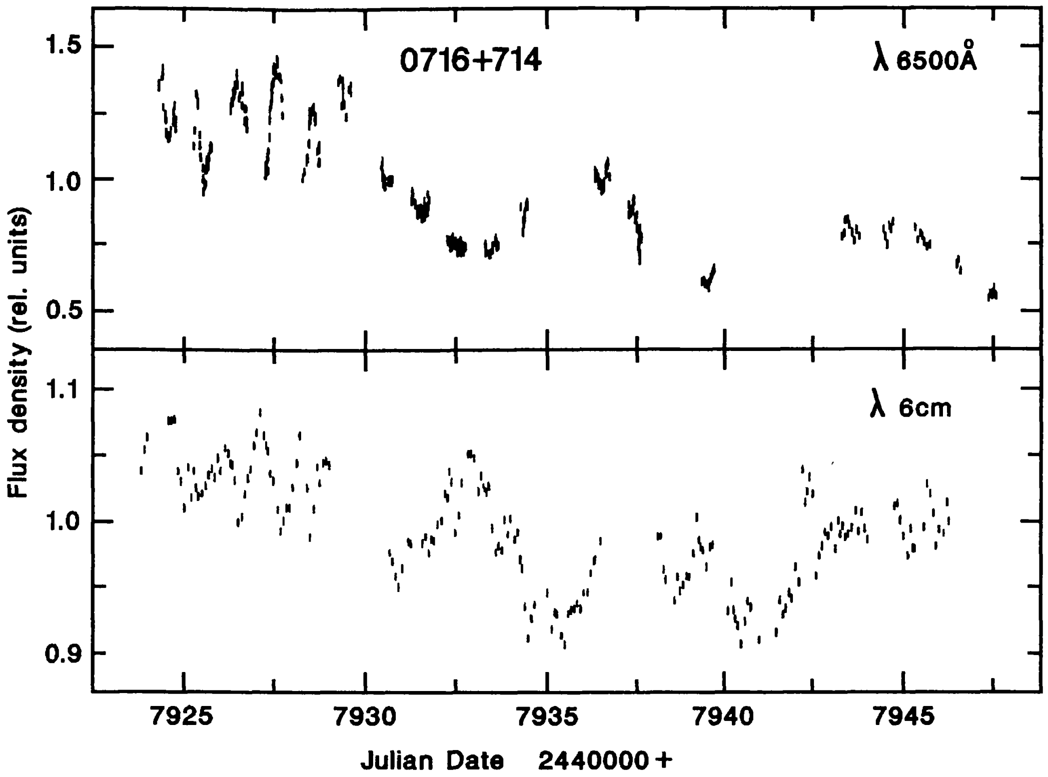

Figure 5. Light curves of the BL Lacertae object 0716+714 in the optical (R band) and radio (6 cm). The y-axis is as in Figure 3. The two light curves appear to be correlated.

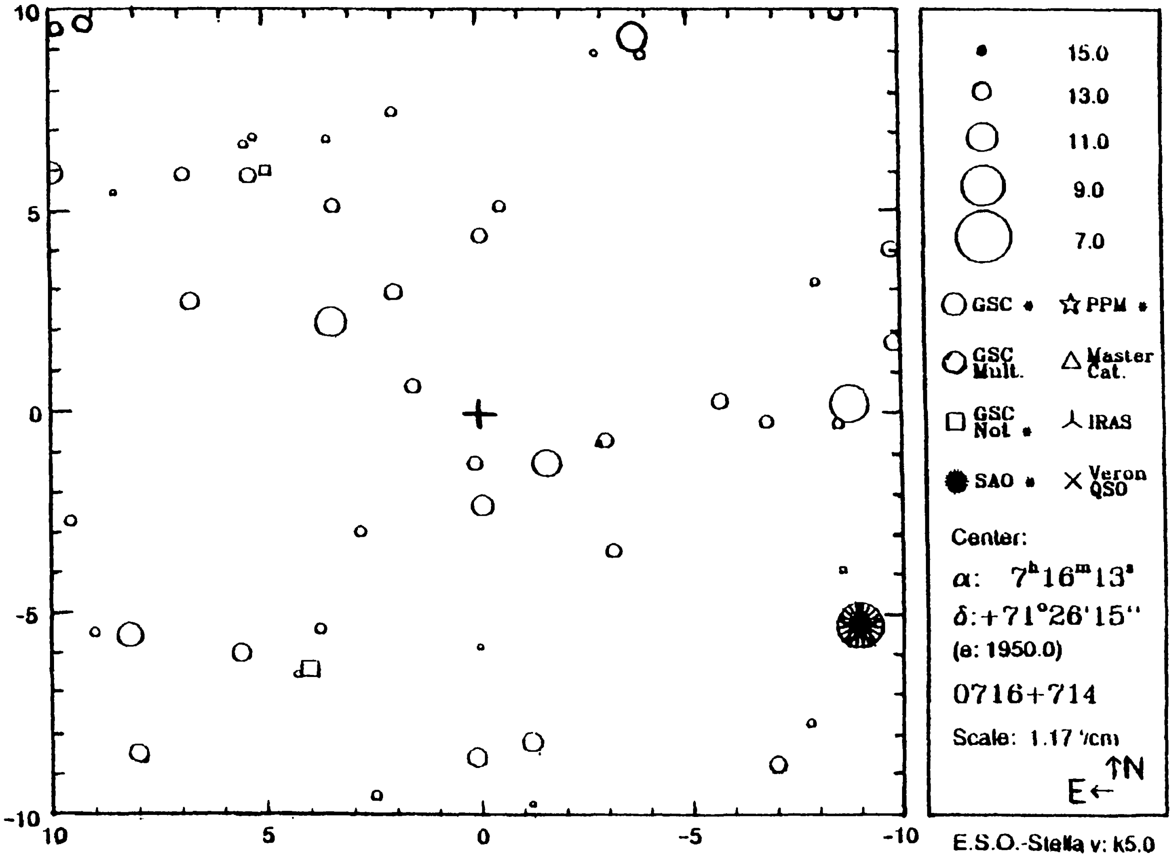

Figure 6. Finder chart for the BL Lacertae object 0716+714.