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DRAMATIC VARIATIONS IN THE POLARIZATION OF BL LACERTAE: SHOCKS AND GAS?

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ABSTRACT

During the series of radio bursts in BL Lacertae which started in late 1979, the polarization exhibited a dramatic evolution. In the initial bursts, the degree of polarization was generally low, and the polarization position angle showed a large, systematic rotation. The later, smaller amplitude flux density bursts exhibited much higher degrees of polarization; we interpret this as the result of increased ordering of the magnetic field as the emitting region evolved. We have detected a change with time in Faraday rotation of the polarized emission of more than 100 rad m^{-2} which indicates the presence of nonrelativistic gas in or near BL Lacertae. The most recent burst was highly polarized with an intrinsic polarization position angle within a few degrees of the observed orientation of jetlike structures in the source. This is strong evidence for an axial compression, perhaps the formation of a shock, in the jetlike emitting region of BL Lacertae.

Subject headings: BL Lacertae objects — polarization — radio sources: variable

I. INTRODUCTION

Starting in late 1979, BL Lacertae has undergone a series of large-amplitude radio bursts. This activity was preceded by a 3 year period of relative inactivity (the previous large flux density outburst in BL Lacertae was in 1976), so these events have afforded an unusual opportunity to study the radio outburst phenomenon. A series of very long baseline interferometry (VLBI) experiments have shown the existence of apparent, faster than light motions of the radio-emitting regions along a position angle of approximately 10° (Mutel, Aller, and Phillips 1981; Phillips and Mutel 1982); during the initial large bursts in 1980, a rapid, large-amplitude rotation with time of the polarization position angle was observed (Aller, Hodge, and Aller 1981). This *Letter* reports on more recent polarization activity in the object: in particular, time-variable Faraday rotation of the polarized emission and evidence from the polarization characteristics of the most recent burst for the *in situ* formation of a new source component within the radio jet.

II. OBSERVATIONS

The results reported here were obtained using the automated 26 m paraboloid of the University of Michigan Radio Astronomy Observatory operating at 4.8, 8.0, and 14.5 GHz. The on-off type of observing technique and wide-band radiometer systems used for the observations have been described elsewhere (Aller 1970*a*; Aller, Aller, and Hodge 1981). The observational results are presented in Figure 1 as daily averages of the data (typically 8–12 on-off measurements each day). The lower three panels show the observed data corrected for instrumental polarization and antenna gain variations. The uncertainties shown are standard deviations based upon the internal scatter of the observations on each day, and the polarization uncertainties include an 0.1% uncertainty to account for the day-to-day instability of the instrumental polarization (see Aller 1970*a*). Polarization position angle measurements with uncertainties of more than 14° are not included in the figure. In the top panel, the observed polarization position angles at 4.8, 8.0, and 14.5 GHz have been changed by $+52^{\circ}.4$, $+18^{\circ}.9$, and $+5^{\circ}.7$, respectively, in order to remove the effect of a rotation measure of -234 rad m^{-2} derived from our data during the most recent outburst.

The behavior of the radio polarization changed during the series of flux density bursts. In the initial, large-amplitude flux outbursts, the degree of polarization was relatively low (never exceeding 5%), and the polarization position angle exhibited large excursions, including the rapid rotation event reported earlier (Aller, Hodge, and Aller 1981). The subsequent bursts were much more highly polarized, and in fact the highest polarized flux was observed during the smallest amplitude burst which started in late 1981. After 1980 the polarization position angle became relatively stable, with the exception of the sudden jump in 1981 September–October. The behavior of the polarization suggests that the magnetic field structure in the sychrotron-emitting region became increasingly well ordered as the region evolved.

During the flux density burst which started in 1981 August, the observed polarization position angles ex-

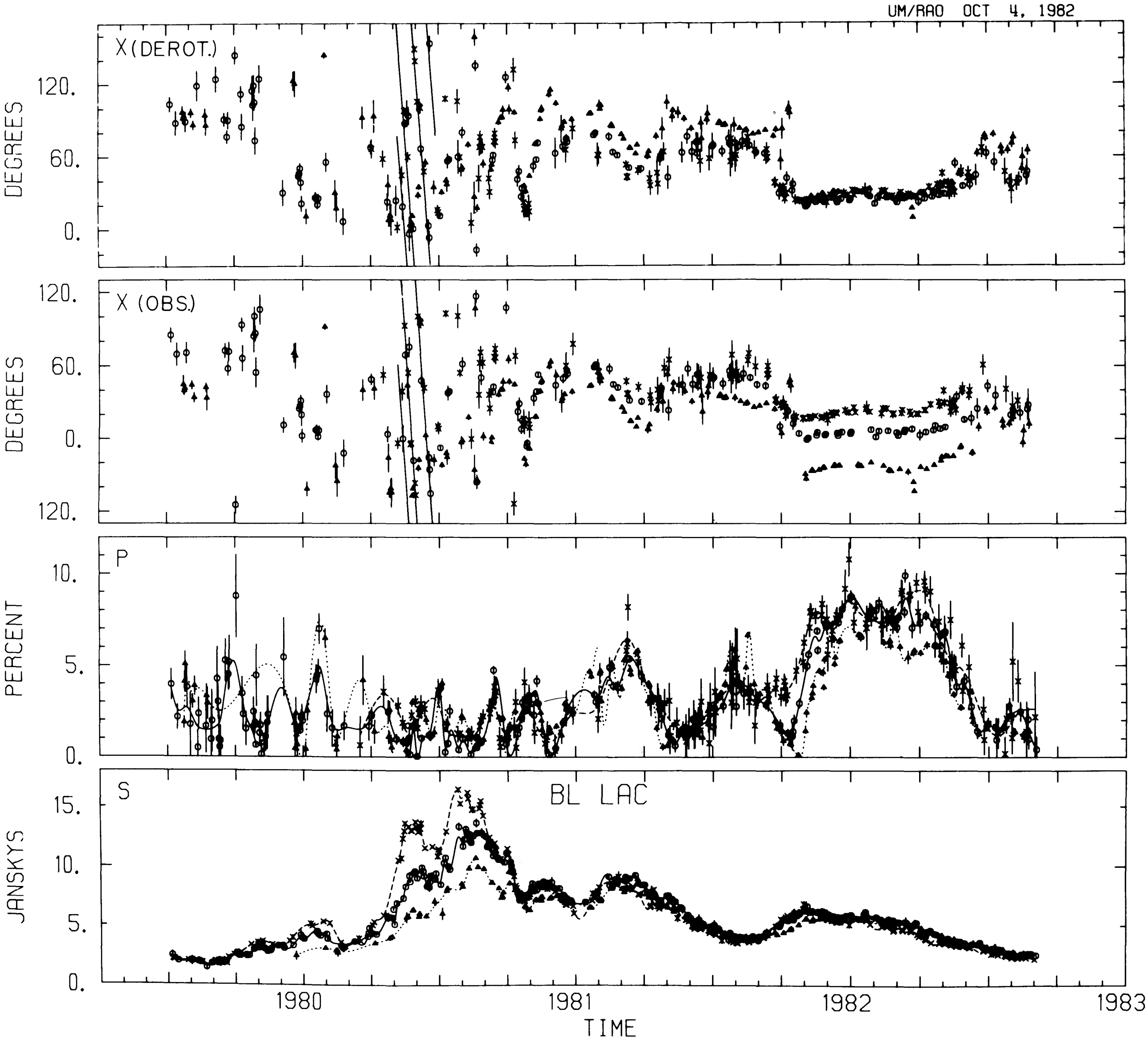

FIG. 1.—Daily averages of the flux density and polarization of BL Lacertae at 4.8, 8.0, and 14.5 GHz (shown by ▲, O, and × respectively) during the recent series of outbursts. From bottom to top the panels show the total flux density, the degree of polarization, the observed polarization position angle, and the position angle data derotated using a rotation measure of -234 rad m^{-2}. The curves in the lower two panels are smoothing cubic splines (Reinsch 1967). The rapid rotation of the polarization position angle reported earlier is indicated by parallel lines.

hibit a well-defined wavelength-squared dependence such as would be produced by Faraday rotation. The top panel of Figure 1 shows the result of removing the average value of the Faraday rotation during the burst. This "correction" removes the wavelength-dependent position angle separation during the burst which is consistent with the hypothesis of Faraday rotation. However, before 1981 September, BL Lacertae had a different rotation measure. Figure 2 displays the rotation measures and intrinsic position angles derived from monthly averages of our triple-frequency data. The uncertainties indicated in this figure are the *larger* of the scatter of the data about a wavelength-squared law and the uncertainties predicted on the basis of the internal scatter of the data at each frequency during each month. The horizontal lines represent the average values of the rotation measure before and during the most recent burst. The difference between the average rotation mea-

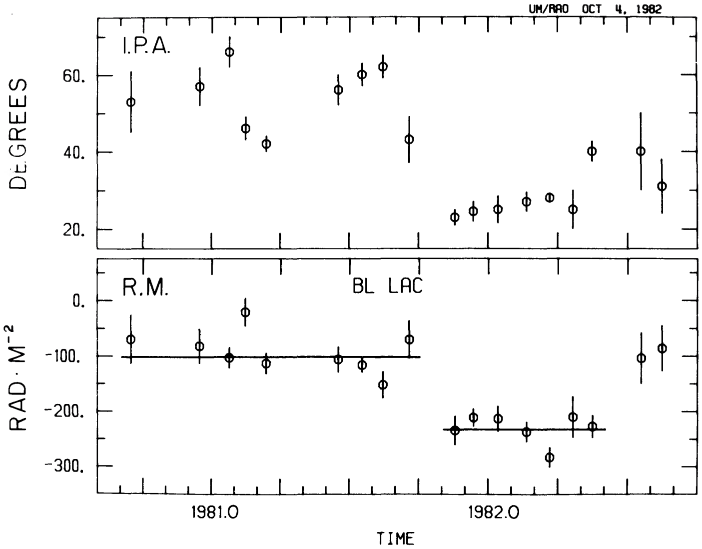

FIG. 2.—The rotation measure and intrinsic position angle of BL Lacertae as a function of time derived from monthly averages of the data at our three frequencies. The standard errors shown are the larger of the internal position angle uncertainties and the standard deviation of the data about a wavelength-squared law.

sures is -131 ± 15 rad m^{-2}; and there was also a sudden change in the intrinsic position angle during the onset of the burst in late 1981.

III. DISCUSSION

Prior to 1981 the polarization of BL Lacertae varied rapidly, and the spectra exhibited by the total flux data indicate the presence of significant self-absorption in the emitting region (Aller, Hodge, and Aller 1981). Faraday rotation effects of the magnitude discussed in this *Letter* may have been present during this earlier period, but the complexity of the polarization variations prevents us from making an accurate determination from our data. The discussion below is limited to the period after 1980 when the polarization position angle behavior is better defined by our data.

We believe that the best interpretation of the sudden change of the Faraday rotation measure in 1981 October is that the new outburst was produced by a new, spatially separated component in the radio jet, and that the change in rotation measure was the result of the different line-of-sight path through the magnetoactive plasma in the vicinity of the radio source. It is not possible to clearly separate out the amount of Faraday rotation associated directly with BL Lacertae, since the rotation measures we have observed in BL Lacertae are comparable to those expected to be produced within our own Galaxy in that direction (e.g., Gardner and Davies 1966). However, the sudden *change* in the rotation measure appears to have occurred within or near BL Lacertae and not in our Galaxy. This change in rotation measure was coincident with the onset of the outburst in the source; and the very small angular extent of the microwave-emitting region, of the order of 5 milli-arcseconds (Phillips and Mutel 1982), would correspond to a physical size of only 100 AU even at a distance of 20 kpc. The hypothesis that the change in rotation measure was produced by a change in the line of sight through our Galaxy would require that an extremely small, dense H II region lie in the direction of BL Lacertae (galactic latitude = $-10^\circ\!.5$). On the other hand, an H II region in the vicinity of the nucleus of BL Lacertae with a diameter of 1 pc, an electron density of 1 cm^{-3}, and a field strength of 2×10^{-4} gauss could account for the observed change in the rotation measure of -131 rad m^{-2}.

This single "probe" of the vicinity of BL Lacertae does not place limits on how the cool gas responsible for the Faraday rotation might be distributed. An independent measurement of the Faraday rotation of BL Lacertae made in 1981 May at frequencies of 1.465 and 1.665 GHz yielded a rotation measure of -205 rad m^{-2} and an intrinsic position angle of 92° (Rudnick and Jones 1983). These lower frequency emissions may have been produced in a different part of the radio-emitting region, so that the different results between the different spectral regions could be accounted for by variations in the rotation measure across the source.

One limit given by our data is that most of the observed Faraday rotation occurred outside of the radio-emitting region. During the evolution of the outburst, the degree of polarization at all three frequencies changed by more than a factor of 5, indicating a significant change in the degree of order of the magnetic field within the emitting region. In contrast, the rotation measure, which depends upon the magnetic field in the plasma producing the rotation, changed little during most of the burst. The frequency dependence of the degree of polarization during the burst could have been produced by depolarization due to internal Faraday rotation; but both the spectrum of the total flux density and the behavior of the degree of polarization during the burst indicate that at least part of the emitting region was opaque, which could also produce the observed depolarization (Aller 1970*b*).

During the most recent burst, the intrinsic position angles ranged only from 23° ± 2° in 1981 November to 28° ± 1° in 1982 March (see Fig. 2). These position angles indicate that the magnetic field in the emitting region was apparently nearly perpendicular to the projected orientation of the jet of 10° (Phillips and Mutel 1982). We believe that the polarization position angle of the burst emission is closer to the jet orientation than indicated by the above numbers because one must remove the polarized emission arising from the other emitting regions in the source from the total observed polarized emission. This type of "correction" is model dependent, but to estimate this effect, we averaged the Stokes parameters observed during 1981 June, July, and August at each of the three frequencies and subtracted these averages from the observations during the most recent outburst. The derived rotation measures did not change during the burst, but the intrinsic polarization position angles were rotated by $-8°$, implying that the polarization position angles of the emitting region ranged from only 5° to 10° from the jet axis. Within the observational uncertainties, the data are consistent with the hypothesis that the polarization is aligned along the projected jet axis.

One "traditional" interpretation of the "hot spots" observed by VLBI experiments in radio jets is that groups of radiating particles, accelerated in some central engine in the throat of the jet, propagate along the jet, and that the bright regions correspond to these concentrations of emitting particles. The polarization behavior of BL Lacertae suggests an alternative scenario in which relativistic particles traveling in a continuous stream down the jet are compressed or reaccelerated at various sites in the jet producing the observed bright regions.

The polarization and spectral data together with the morphological data from VLBI for BL Lacertae provide good evidence for the reacceleration of emitting particles and thus the *in situ* formation of new source components along radio jets. The high degree of order and orientation of the magnetic field in the recent BL Lacertae outburst could have been produced by a compression of material along the jet axis. A shock produced either by an obstruction, such as a pinch in the jet, or by a stream of faster particles overtaking slower ones would appear to be an excellent candidate mechanism for producing the observed phenomena in BL Lacertae. There may be two types of "outbursts" in extragalactic variable sources. The first type is produced by the sudden increase in the rate of particle acceleration in the central engine of the source and is characterized by significant self-absorption evident in the total flux spectra, relatively disordered magnetic field structures, and the rotation phenomenon; examples might be the events in BL Lacertae during 1980. The second type of burst is produced *in situ* along the jet as the result of the "rethermalization" of the relativistic gas streaming down the jet. The two bursts in 1981 in BL Lacertae, characterized by relatively flat spectra and by well-ordered, stable magnetic field structures, would be examples of this second type of burst.

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