The Optical Polarization Properties of X-ray Selected BL Lacertae Objects

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ABSTRACT

We discuss the optical polarization properties of X-ray selected BL Lacertae objects (XSBLs) as determined from three years of monitoring the polarization of 37 BL Lac objects and candidates. The observed objects include a complete X-ray flux limited sample drawn from the Einstein Extended Medium Sensitivity Survey (EMSS). We find that the majority of the XSBLs classified solely on the appearance of the their optical spectra are true members of the class of BL Lacertae objects since they possess intrinsically polarized and variable continua. The duty cycle of polarized emission (fraction of time spent with the degree of polarization greater than 4%) from XSBLs is 40%. While XSBLs have variable polarized emission, the majority (≈ 85%) have stable or preferred polarization position angles on time scales at least as long as three years. This reflects stability in the geometry of the region emitting the linearly polarized optical emission. We describe the observed spectral dependence of the degree of polarization and discuss some of the possible mechanisms producing the observed characteristics. While dilution of the polarized emission by the host galaxy starlight is certainly present in some objects, we demonstrate that the average polarization properties of XSBLs derived from our observations are not drastically affected by this effect. While the confirmed BL Lac objects are shown to be photometric variables, the objects in our monitored sample did not display the larger than one magnitude variations generally used to characterize the optical variability of radio selected BL Lacertae objects or blazars in general.

Subject headings: BL Lacertae Objects – Polarization – Photometry
1. Introduction

In 1987 we began a program to measure and monitor the optical polarization of X-ray selected BL Lacertae objects (XSBLs). The majority of XSBLs have received their classification on the basis of essentially one criterion: that optical spectroscopy of objects within the X-ray position error box of an X-ray source revealed an object that presented some evidence of having a non-thermal continuum by exhibiting a “featureless” spectrum. We are interested in determining whether these X-ray selected objects are really members of the class of BL Lac objects, possessing intrinsically variable polarized emission indicative of optical synchrotron radiation. Evidence has been presented indicating that XSBLs have significant differences in their observed properties from radio selected BL Lac objects (RSBLs) (Stocke et al. 1985). These differences included apparently less variable and less polarized optical emission. Although the studied sample of XSBLs consisted of only eight objects, the apparent differences led to questions about the relationship between the objects selected from surveys made at the two different bands.

Work by other authors examines the optical spectra, flux variability, and radio properties of XSBLs (e.g. Stocke et al. 1985; Stocke et al. 1990; Morris et al. 1991; Stocke et al. 1991; Perlman & Stocke 1993; Laurent-Muehleisen et al. 1993). A previous examination of the polarization properties of an incomplete sample of XSBLs was presented by Schwartz et al. (1989). Our work (Jannuzi 1990; presented here and in two related papers) is the most extensive and systematic examination of the optical polarization properties of a complete sample of XSBLs. Together, these studies provide the data necessary to compare the radio and X-ray selected objects.

We have divided the presentation of our results into three papers. In Jannuzi, Smith, & Elston (1993, paper I) we present our definitions of the terms X-ray and radio selected BL Lac, highly polarized quasar (HPQ), and blazar; describe the observing techniques
and procedures used in obtaining our polarimetry and photometry data; describe the composition of the X-ray selected and radio selected samples of BL Lac objects that we will use in our general study of the optical polarization properties of all BL Lac objects; and present all of our polarimetry and photometry data. Jannuzi, Elston, & Smith (1994, paper III) compare the optical polarization properties of XSBLs with RSBLs as part of our efforts to learn more about the entire class. In this paper (paper II), we describe the general optical polarization properties of XSBLs as derived from our observations. In §2 we present the general polarization characteristics of XSBLs. We describe the detection, maximum observed polarization, variability, and frequency dependence of the polarization. We examine the possible effects of the host galaxy starlight on the observed polarization properties of BL Lac objects in §2.4. In §3 we present the results of our photometry including a discussion of detected variability. For a discussion of the properties of individual objects see paper I. We discuss the proper classification of these objects in §4. In §5 we summarize the results of this paper.

2. Polarimetry of XSBLs

We have measured the polarization of all of the XSBLs in our sample and monitored their polarization. Our monitored objects include the complete X-ray flux limited sample compiled as part of the Einstein Extended Medium Sensitivity Survey (EMSS, Gioia et al. 1990; Stocke et al. 1989; Stocke et al. 1990; Stocke et al. 1991; Morris et al. 1991). The program objects are listed in Table 1 and their selection is discussed in paper I. Positions, finding charts, and photometrically calibrated comparison stars for the monitored objects are presented in Smith, Jannuzi, & Elston (1991). While every effort was made to observe all of the objects as many times as possible, there are disparities in the degree objects were monitored. This was the result of several constraints. First, the bulk of our monitoring
was performed with the Steward Observatory (SO) 1.54 m telescope, which cannot observe objects with declinations greater than 61°. Second, the fainter objects ($m_v > 19.0$) could be observed at the SO 1.52 m and 1.54 m telescope only if the weather and seeing were excellent. Third, objects with low declinations were obviously not as easy to monitor from Steward observatory as objects at higher declinations. Despite these restrictions, we were able to monitor the majority of the EMSS XSBLs. We note that our monitoring data are not biased by the past behavior of the objects in the sample. It is well known that the early polarimetry of RSBLs (especially for the published data) is biased by the “hot object” effect. Objects which were observed to be highly polarized tended to be more extensively monitored than objects which had low polarizations when first observed. This problem is still affecting our knowledge of the polarization properties of quasars. In our study of XSBLs we have attempted to observe all of the observable program objects during each night of observation, regardless of their past polarization history. When possible, we have performed multicolor polarimetry in order to examine the frequency dependence of the percent polarization and position angle.

2.1. Are XSBLs Polarized?

The results of our polarization and photometry observations of the individual objects are summarized in Table 1. In column (2) we indicate to which X-ray selected sample an object belongs: HEAO-A2 = HEAO-1 A-2 high latitude sample, HEAO-NRL = NRL HEAO-1 catalogue as identified by the Large Area Sky Survey, EMSS = EMSS BL Lac object or candidate BL Lac object, C-EMSS identifies objects which are members of the complete subsample of EMSS BL Lac objects (see paper I for a discussion of these samples).

Prior to our observations, the majority of our program objects had not been observed
for polarized emission. We observed 31 of these objects to be polarized on at least one occasion. We were able to make significant observations for 21 of the 22 members of the C-EMSS. We deem an observation “significant” if it yields a three sigma detection of polarized emission \( P/\sigma_p > 3 \) or a two sigma limit of 4%. We define our two sigma limits to be the measured percent polarization plus two times the uncertainty in the measurement \( P_{\text{obs}} + [2 \times \sigma_p] < 4\% \), where \( P_{\text{obs}} \) is the observed percent polarization without correction for statistical bias). We chose a limit of 4% because we were generally able to obtain limits of this quality given our observational constraints.

If “ISP” appears in column (12), significant interstellar polarization was detected in the field of the object. Polarization measurements were made of stars in the fields of all the observed XSBLs in order to check for interstellar polarization caused by dust along the line of sight. The measured stars included the photometry comparison stars described in Smith et al. (1991). The results of these measurements are discussed further in paper I. For two objects (MS 0205.7+3509 and MS 0419.3+1943) the comparison stars were observed to be polarized with position angles agreeing with the polarization position angles of the BL Lac object candidates and conclusive variability in the polarization of these objects was not detected. We do not consider either of these objects to have shown intrinsic polarization.

We also note that the following objects were detected to be polarized on only one occasion or were only marginal detections: MS 0607.9+7108, H 1101−232, MS 1229.2+6430, MS 1235.4+6315, MS 2336.5+0517, and MS 2347.4+1924.

2.2. Variability of Polarization

Our polarization measurements determine both the percent polarization \( P \) and position angle \( \theta \) of the electric field vector of the linearly polarized light. For the majority
of the program objects, particularly those with declinations less than 60°, we have multiple observations and can examine whether or not the percent polarization and/or position angle vary with time. Our observing runs were generally a few days in duration and spaced at roughly monthly intervals. The “variability” column of Table 1 (column 11) contains a set of codes describing for each object its variability as determined from our observations. The symbols mean the following:

\[ p = \text{detected significant polarization intrinsic to the source, but no significant variation in the percent polarization has been observed.} \]

\[ P = \text{detected significant polarization intrinsic to the source and the percent polarization has been observed to vary significantly (} \Delta P > 2\sigma_p \text{).} \]

\[ \theta_{\text{pref}} = \text{during the years of monitoring the position angle of the polarization was not observed to vary significantly (} \Delta \theta < 2\sigma_\theta \text{).} \]

\[ \Theta = \text{the position angle of the polarization has been confirmed to be variable (} \Delta \theta > 2\sigma_\theta \text{).} \]

\[ \Theta_{\text{pref}} (\Theta_{\text{stable}}) = \text{during the years of monitoring, the position angle of the polarization was observed to vary significantly, but only over a limited range. We say that it has a stable polarization position angle if the object’s behavior indicates it might have a preferred position angle, but our observations do not meet our defined requirements for designating the object as having a preferred angle of polarization (see §2.2.3 for the definition).} \]

Note that in general the minimum separation between observations is \( \sim 1 \) day, so that we are not able to detect or characterize variations on shorter time scales. In Figure 1 we present plots of \( m_v, P, \) and \( \theta \) versus the date of observation for six of the monitored objects.

2.2.1. Maximum Observed Polarization, \( P_m \)
We will be comparing in paper III the polarization properties of the XSBLs to various samples of RSBLs, HPQs, and blazars. One of the properties we will compare is $P_m$, the maximum percent polarization ever observed for an object. Ideally we would always compare polarized fluxes or luminosities, but the advantage of percent polarization is that it is a quantity that can be measured even under nonphotometric conditions and does not depend on the availability of a measured redshift for the object. When possible we also made photometric observations which allow the determination of $S_p$, the polarized flux. We list in column (3) of Table 1 the maximum observed white light (unfiltered) percent polarization for each of our program objects. The variability of the object, thoroughness of monitoring, and dilution of the polarized nonthermal emission by the unpolarized host galaxy starlight may affect the observed $P_m$. These issues will be discussed when we compare the maximum observed polarizations of XSBLs to those of RSBLs (§ 2.4 and paper III). When a limit is listed for $P_m$, it is the lowest two sigma limit (as defined in § 2.1) obtained for the polarization of the object.

For eleven objects we were able to make polarization measurements through color filters (see paper I for a description of the filters). For ten objects the maximum observed polarization at $U$ or $B$ was greater than the white light $P_m$. In column (5) of Table 1, we list the maximum observed percent polarization at any optical frequency if it was greater than the white light measurement. The observed values of $P_m$ range from 1.3 to 16%, considerably below the maximum values observed for some RSBLs and blazars (30 to 40%). H 1722+119 has the highest observed percent polarization of any XSBL ($U$-band polarization of 18%).

### 2.2.2. The Duty Cycle of the Percent Polarization
If we make the reasonable assumption that all of the XSBLs in the C-EMSS are intrinsically members of the same class of object, then a single set of polarization measurements of this sample gives us a “snapshot” determination of the duty cycle of polarization for XSBLs. We define the duty cycle as the fraction of the sample that for a given epoch of observation has percent polarizations above a given cutoff level. The duty cycle is frequently defined as what fraction of the time a member of the class is highly polarized (above the cutoff value). We are making the assumption that the temporal distribution of polarization in a single object is equivalent to the distribution of polarization measured in all objects in the class. Similar calculations have been done for RSBLs (Kühr & Schmidt 1990) and for all blazars (Impey & Tapia 1990; Fugmann & Meisenheimer 1988). Because the majority of our observed two sigma limits for nondetections are at 4%, we have chosen that value as the dividing line in our duty cycle calculation. This is slightly higher than the previously adopted boundary of 3% for detection of significant polarization (e.g. Moore & Stockman 1984). The 3% value was chosen as an aid in discriminating against objects polarized by interstellar dust (typical interstellar values due to dichroic absorption are less than < 2%; Mathewson & Ford 1970). The calculation of the duty cycles for blazars or RSBLs is not significantly changed if we use a cut off of 4%.

For the C-EMSS we have multiple significant observations for twenty of the twenty-two objects. We have computed the duty cycle for the first, second, and last epoch of observation of the C-EMSS sample. For some objects the first, second, or last epoch of observation is only an upper limit. For the duty cycle calculation we have assumed that these objects were polarized at the limit value.

For objects that were never observed to be polarized (for the C-EMSS sample, 5), we have considered two possibilities. We first assume that these objects are BL Lac objects and that they have just failed to exhibit the polarized emission when we have observed them.
Under this assumption we have used the limit values as the observed polarization. The second possibility is that these objects are misclassified and we have also calculated the duty cycle for the sample without the inclusion of these objects. For a very few members of the sample, we do not have three epochs of observation and we have assumed that the object had a percent polarization greater than 4%. For example, we were never able to observe MS 1443.5+6349 and we have assumed for the calculations below that this object would have had a polarization greater than 4%. We have calculated the duty cycle of the C-EMSS XSBLs in a manner to avoid at all costs underestimating the amount of time spent at large values of percent polarization. Consequently, we have almost certainly overestimated the duty cycle. We calculated the uncertainties in the duty cycle by considering the one sigma range of observations for each object. If an object was observed to be 3.5% $\pm$ 0.7% polarized, the object was counted as less than four percent, but contributed to the positive uncertainty.

The computed values for the three epochs are $41^{+14}_{-27}$%, $32^{+14}_{-13}$%, and $46^{+10}_{-14}$% for the first, second, and last observational epoch, respectively. If we restrict ourselves to those objects in the C-EMSS which were observed on at least one epoch to have intrinsic polarized emission, the sample size decreases to sixteen objects and the new duty cycle estimates are $44^{+6}_{-31}$%, $25^{+19}_{-6}$%, and $50^{+13}_{-13}$%. The EMSS is biased against objects of high X-ray flux (see paper I). If we add the HEAO-A2 objects to the C-EMSS, the duty cycles calculated from the first and last epochs of observation are $38^{+11}_{-23}$% and $42^{+8}_{-12}$% (and excluding objects never detected to be polarized, $38^{+5}_{-23}$% and $48^{+100}_{-10}$%). For the entire program sample (34 objects with detections or two sigma limits of better than 4%), the first and last epoch duty cycles are $32^{+9}_{-9}$% and $47^{+9}_{-26}$%. If we restrict the calculation to those objects with confirmed detections on at least one epoch, our sample size drops to twenty-nine objects and the resulting duty cycles are $38^{+10}_{-10}$% and $45^{+10}_{-21}$%. We adopt 40%, the average of the values determined for both the EMSS and C-EMSS plus HEAO-A2 sample, as the duty cycle of
The measured duty cycles are not the consequence of some small population of highly polarized ($P > 4\%$) XSBLs mixed in with a group of objects that are not capable of being highly polarized. The majority of the program objects were observed to be highly polarized on at least one occasion (20 out of 34). If we restrict our consideration to the objects with detected intrinsic polarized emission (the confirmed BL Lac objects), $69^{+13}_{-10}\%$ were observed to be highly polarized at least once (20 out of 29, with the error reflecting that some objects were within one sigma of the dividing line of 4\% polarization).

2.2.3. Preferred Polarization Position Angles

A substantial number of the XSBLs in our monitoring program have exhibited a preference for a limited range of polarization position angles. We describe an object as having a preferred polarization position angle if during our three years of monitoring the observed position angles are concentrated to a limited range of angles. This does not mean that these objects might not lose this preference over time or develop a new preferred position angle in the decades ahead. To test for such behavior, even longer periods of monitoring are required.

While our observing runs were usually separated by a month or more, many of the objects were observed repeatedly during a two to five day run. It could be argued that observations within one week are not “independent” and that we should not let four or five observations in one week skew our impression of the stability of the polarization position angle. Unfortunately it is not clear what is enough separation in time to call two observations “independent.” We can, however, still address the question of preferred position angles over the time period of our study by limiting ourselves to a consideration
of well-observed objects. We consider an object to be well-observed for position angle variability if the following criteria are met:

1.) The object must have been observed to be significantly polarized during at least six separate observing runs. Observing runs are generally two to seven days in length and are separated by at least three weeks.

2.) We must have a significant baseline of observations of the object. We choose the arbitrary number of 20 months separation between the first and last observation.

Table 2 lists the XSBLs which meet these criteria. The objects MS 0737.9+7441 and H 1722+119 are also included in Table 2 for reasons explained below. The individual columns of Table 2 contain the following information: (1) object name, (2) sample membership, (3) variability code as defined for Table 1, (4) the number of observation epochs (nights observed), (5) the number of observing runs during which the object was significantly polarized, (6) the observed range of the polarization position angle, (7) the mean position angle calculated by including only one observation from each observing run, (8) the variance of the observed distribution of position angles, (9) the average deviation from the mean, (10) the time in months between the first and last observations of the object.

For our study, we describe objects which meet the following criteria as having preferred position angles: 1.) They are well observed for position angle variability (defined above), 2.) They have average deviations from the mean angle of less than $20^\circ$. This last criterion is a quantitative means of expressing the observation that the range of variability of the position angle is limited. What we mean by limited range of $\theta$ is best exemplified by the data for MS 2143.4+0704. Examination of Figures 1 and 2 shows that over 22 months of observation, the position angle of the polarization of this BL Lac object did not vary by more than $20^\circ$. 
Under this definition, 11 of the 15 objects in Table 2 have preferred position angles. MS 0737.9+7441 and H 1722+119 have observed position angles which do not vary over a wide range, but do not meet the first criterion listed above. We describe them as having stable position angles. We only have four epochs of detected polarized emission for MS 0737.9+7441 and the baseline of observations for both MS 0737.9+7441 and H 1722+119 is only one year. H 1722+119 was added late to our study when its identification as an XSBL was available in 1989 (Brissenden et al. 1990).

Of the 22 C-EMSS BL Lac objects, seven are included in our well-studied sample. An amazing six out of seven (86%) have preferred position angles. In fact 85% of the entire well-studied sample (11 out of 13) have preferred position angles. All but one of the objects (MS 0257.9+3429) have confirmed variable position angles, but the range of variation is limited. In Figure 2 we present plots of the normalized Stokes parameters (U/I vs. Q/I) for the objects in the well-studied sample. We have plotted all of our white light polarization observations for each object.

2.3. Frequency Dependence of the Polarization

We were able to obtain multicolor polarimetry for 11 of our program objects. A range of frequency-dependent behavior was observed. In an effort to quantitatively describe the observed frequency dependence of the percent polarization (FDP) for these objects we use the parameter

\[ P_\nu = \frac{d(\log P)}{d(\log \nu)}. \]

We characterize the frequency dependence of the polarization position angle with the analogous parameter
\[ \theta_\nu = \frac{d\theta}{d(\log \nu)}. \]

Additional description of these parameters can be found in Smith & Sitko (1991). Table 3 summarizes the frequency-dependent behavior of the polarization for the observed objects. The column heading symbols mean the following:

\[ P_\nu(+) = \text{number of observations for which } P_\nu - 2 \times \sigma(P_\nu) > 0. \] This corresponds to the number of times the percent polarization was observed to increase (decrease) with the frequency (wavelength) of observation.

\[ P_\nu(-) = \text{number of observations for which } P_\nu + 2 \times \sigma(P_\nu) < 0. \] This corresponds to the number of times the percent polarization was observed to decrease (increase) with the frequency (wavelength) of observation.

\[ P_\nu > 0 = \text{number of times } P_\nu > 0. \] This is the same \( P_\nu(+) \) without the significance restriction.

\[ \text{max}(P_B/P_I) = \text{the maximum ratio between the } B\text{-band percent polarization and the } I\text{-band percent polarization for those observations where } P_\nu - 2 \times \sigma(P_\nu) > 0. \]

\[ |\theta_\nu| = \text{number of times that either } \theta_\nu - 2 \times \sigma(\theta_\nu) > 0 \text{ or } \theta_\nu + 2 \times \sigma(\theta_\nu) < 0. \]

\[ \text{max}(\theta_B - \theta_I) = \text{maximum difference (in degrees) between the } B\text{-band and } I\text{-band polarization position angles when } \theta_\nu - 2 \times \sigma(\theta_\nu) > 0 \text{ or } \theta_\nu + 2 \times \sigma(\theta_\nu) < 0. \]

The general results are quite clear. Whenever significant FDP is detected the sense is always positive, i.e. the percent polarization increases with frequency. Frequency dependence of the polarization position angle (FD\( \theta \)) was only detected at better than the 3 \( \sigma \) confidence level on one occasion (H 2154–304 on 1988 October 29).

### 2.4. Dilution of the Polarized Emission by the Host Galaxy
Most of the XSBLs have evidence of the underlying host galaxy in their optical spectra as demonstrated by the strength of stellar absorption features and the 4000 Å break in their spectra (Stocke et al. 1985; Morris et al. 1991). In this subsection we examine the possible effects of the host galaxy starlight on the observed polarization of the synchrotron emission from our sample of BL Lac candidates and objects.

Unpolarized starlight of the elliptical host galaxy (virtually all of the identified BL Lac object hosts are elliptical galaxies, see for example Abraham 1991a,b and Ulrich 1989) “dilutes” the percent polarization of the synchrotron source that dominates the observed properties of BL Lac objects. Dilution is most pronounced at longer wavelengths where the intrinsically red spectral energy distribution of the host galaxy contributes more flux. However, the magnitude of the effect on the observed polarization will also depend on the relative brightness and steepness of the power law of the nonthermal emission.

We have generated model BL Lac object spectra consisting of elliptical galaxies with an added power law ($F_\nu \propto \nu^{-\alpha}$) and calculated the observed percent polarization relative to the intrinsic polarization of the synchrotron source. Cruz-Gonzalez & Huchra (1984) observed BL Lac objects to have a range of power law indices ($\alpha$) of 1.01 to 3.93. The vast majority falling in the range 1.0 to 2.0 and with a mean of 1.89±0.79. H 2154−304 has an observed optical spectral index between 0.7 and 0.8. We have generated models with $\alpha$ ranging from the extremely low value of 0.7 to 2.0, close to the mean observed value. For the elliptical galaxy we used the spectrum of NGC 4889 provided in Kennicutt (1992) supplemented at the long and short wavelength ends by the bulge template of Coleman, Wu, & Weedman (1980).

The relative brightness of the nonthermal emission to the galactic starlight must also be set. We have chosen to define this as a function of the strength of the 4000 Å break in the observed total flux from the object since this was used as one of the selection criteria.
for the EMSS sample of XSBLs (see paper I and Morris et al. 1991). For our model spectra the “break strength” is defined as the flux difference above and below 4000 Å divided by the flux longward of 4000 Å (specifically two flux windows were used, 3910 to 3990 Å and 4010 to 4090 Å). In the EMSS sample all of the objects had to have 4000 Å breaks less than 25%.

In Figure 3 we have displayed the ratio of the the observed polarization to the intrinsic percent polarization of the synchrotron source for various combinations of power law nonthermal sources and an elliptical host galaxy for a BL Lac object at a redshift of 0.2. Three groups of four plots are shown. Each group corresponds to a different choice of the strength of the 4000 Å break in the spectrum of the BL Lac object. Plots are shown for break strengths of 5, 15 and 25% (the maximum value any object in the EMSS sample could have). Within each group, the four plots correspond to different values of the power law spectral index, $\alpha$, of the nonthermal component. Note that the various models at a given break strength (differing spectral index) will have different ratios of nonthermal to galaxy flux. The specific values of the spectral index shown in the figure are $\alpha = 0.7, 1.1, 1.5$ and 1.9. This choice covers the bulk of the observed range of spectral indices for BL Lac objects and includes models that show the maximum effect that dilution by the host galaxy can have on the polarization (the $\alpha = 0.7$ models). We have not included models for large values of spectral index since in these cases (even for the break strength of 25%) the possible effects of dilution become unimportant. Note that for smaller break strengths and/or steeper spectral indices (i.e. when the nonthermal component is a larger fraction of the total emission) the effects of dilution on the observed polarization properties greatly decrease.

2.4.1. How Does Dilution affect $P_m$?
It has been suggested that the low observed percent polarizations of the XSBLs result from dilution of the polarization by the host galaxy (Stocke et al. 1985). This would be consistent with the flux contribution of the beamed synchrotron component being less for the X-ray selected objects. We contend that while the host galaxy is definitely a greater fraction of the optical emission of the XSBLs, dilution by starlight is not enough to explain the observed differences in the polarization properties of X-ray selected and radio selected BL Lac objects. In this section we discuss arguments that support the contention that for our sample of XSBLs, the observed distribution of white light $P_m$ is not drastically different from the distribution of $P_m$ for the synchrotron continua free of the effects of dilution. A major focus of paper III is a quantified comparison between XSBLs and RSBLs, including the effects of dilution.

For most of the XSBLs with redshifts greater than $z = 0.2$, $U$ and $B$-band polarimetry measures the polarization shortward of the 4000 Å in the rest frame of the object. Assuming that the host galaxy is an elliptical galaxy, then shortward of the break the object’s emission will be dominated by the nonthermal emission and the observed percent polarization is a relatively accurate indication of the intrinsic polarization of the nonthermal source (see Figure 3). We have $B$ or $U$ polarimetry of five XSBLs with redshifts greater than 0.2. In every case, the maximum observed polarization at $U$ and $B$ is within a few percent of the white light value (measured on the same date). As we will see in paper III, the observed differences between the 1 Jy RSBL and C-EMSS XSBL samples are too great to overcome by shifting the observed $P_m$ distribution of the XSBLs by only a few percent.

It is also clear from Figure 3 that if a XSBL shows no frequency dependence in its observed polarization, dilution can not be playing a major role. Even for objects at low redshift the observed frequency dependence is a clue to the amount of dilution that is present (see §2.4.2).
Even in the worst possible situation, where the host galaxy is providing the bulk of the total observed flux and the nonthermal component has an unrealistically flat spectrum ($\alpha = 0.7$) the correction factor that needs to be applied to the white light polarization measurement to get to the intrinsic percent polarization of the nonthermal source is only a factor of 4 to 5. More typical correction factors (for breakstrengths of 10 to 15%, redshifts of sources 0.1 to 0.4, and power laws of 1.3 to 2.0) are less than a factor of two.

2.4.2. Does Dilution Produce the observed FDP?

The general trends exhibited by the frequency dependence of the polarization of XSBLs are generally consistent with what is expected if the optical nonthermal emission from the AGN is diluted by unpolarized starlight from the host galaxy. We learned in §2.3 that if FDP is observed it always is seen with $P_\nu$ positive. If FDP is caused by galactic dilution this would have to be the case (see Figure 3). Since the galactic starlight has a red spectral energy distribution the percent polarization is smaller in the red because the starlight is a larger fraction of the total flux than it is in the blue.

However, dilution by the host galaxies’ starlight can not explain all of the cases of detected FDP. H 2154−304 is a clear example of an XSBL for which we know that the host galaxy does not significantly affect the observed FDP. Optical and UV polarimetry of this object has presented very compelling evidence that the FDP observed is intrinsic to the synchrotron-emitting region (Smith & Sitko 1991; Smith et al. 1992; Allen et al. 1993). Also, any frequency dependence in $\theta$ can not be explained by starlight of the host galaxy being included within the observational aperture. Dilution by an unpolarized component can only affect the percent polarization, not the position angle of the polarized component. Clearly another mechanism must be responsible for the rare FD$\theta$ observed in H 2154−304
and perhaps in H 0323+022 and H 1219+305.

The optical polarization of the two lowest redshift objects in our sample, H 0548−322 and H 1652+398, are clearly affected by starlight from their host galaxies. Given that neither object has shown significant FDθ, the contribution of the stellar component must be carefully taken into account before advancing any claims for FDP intrinsic to the AGN components of these objects.

Another point to keep in mind is that the host galaxy light is presumably not variable over the short time scales that we have been monitoring these objects. Therefore changes in FDP for a given object must be due to changes in the polarized nonthermal emission. For example, if an XSBL has no FDP when it is faint, but has strong FDP at a later epoch when the object is brighter, then the observed FDP must be due to the synchrotron source. In fact, if dilution were the only mechanism producing FDP there should be a correlation with the presence of FDP and the apparent magnitude of the object. Specifically, as the nonthermal source gets fainter, and assuming that its polarization properties are not strongly dependent on the luminosity of the source, we might expect that the FDP, as measured by the ratio of $P_B/P_I$, should increase as the host galaxy becomes a larger fraction of the observed emission.

It is also interesting to note that, assuming galactic dilution is the only mechanism producing the observe FDP, as $P_\nu$ gets closer to 0 (equivalently, as $P_B/P_I$ gets closer to 1) the affect of dilution on the determination of the intrinsic polarization of the synchrotron source goes down. In other words, for objects with little or no frequency dependence in the observe polarization the white light polarization measurement must be close to being an accurate measurement of the intrinsic polarization of the nonthermal light reaching the observer.

Unfortunately, for most of the objects in our sample we either lack the necessary data
or S/N in the filtered observations to definitively determine if the observed FDP is caused by galactic dilution and/or mechanisms intrinsic to the source of nonthermal emission.
3. Photometry of XSBLs

3.1. Are XSBLs Photometric Variables?

One of the defining criteria of BL Lac objects is that they exhibit flux variability. Our photometry of XSBLs allows us to look for variability and to determine polarized fluxes. The weather permitted accurate V-band photometry on 55 of the 101 nights of observations. On some occasions multiband photometry was obtained for the brighter objects. Other researchers have also been monitoring the variability of these objects. Stocke (1990) reports that all of the C-EMSS BL Lac objects show variability. In the “variability” column of Table 1 we indicate with an “M” objects for which we have confirmed variability from our data alone. We consider that two photometric observations of an object which differ by more than two sigma confirm the variability of the object. If an “M?” appears it means that there is a question about the significance of the variability and the notes on individual objects (paper I) should be consulted. Our data, combined with the observations of Stocke et al. (1991), allow the determination that all of the objects in Table 1 are photometric variables except for MS 0419.3+1943, H 1101−232, MS 1207.9+3945, H 1426+428, MS 2336.5+0517, MS 2342.7−1531, and MS 2347.4+1924. Continued or improved monitoring might detect variability in these latter objects since the long term (greater than two years) behavior of XSBLs is unknown.

We did not observe large or rapid changes in the brightness of these objects. When we did detect variability, the change in brightness was always less than 1.2 magnitudes (peak to peak). In fact, only H 1219+305 was observed to vary by more than one magnitude ($\Delta V = 1.18$). None of the objects could be considered to be optically violent variables. Our photometry is not extensive enough to determine the typical time scales for photometric variability.
3.2. Dependence of Polarization on Total Observed Flux

We have examined our data set to answer the following question: Are increases in percent polarization accompanied by an increase in total and/or polarized flux? There is no fixed rule. Objects are observed to get brighter, have the polarized flux increase, and have $P$ decrease. Objects are observed to get fainter, have the polarized flux decrease, and have $P$ increase. On other occasions, an increase in unpolarized flux is accompanied by a commensurate increase in polarized flux, resulting in an increase of brightness, but no change in the percent polarization.

While a range of behavior is observed, there is a tendency for the maximum observed percent polarization to indicate when the object is experiencing a period of maximum production of polarized flux. However, this might not be significant since higher percent polarizations will yield higher $F_p$'s for objects with limited photometric range.

The data supporting the discussion below are presented in the following columns of Table 1: (6) the apparent magnitude ($m_v$) of the object when the maximum percent polarization ($P_m$) was observed, (7) the white light percent polarization of the object at epoch of its brightest emission ($m_{v, Br}$ or $m_v$ Brightest), (8) the brightest $V$-band magnitude reached by the object (9) the faintest $V$ magnitude observed for the object ($m_{v, Fa}$). When one of these columns has no value it means there are insufficient data. If a value is given for $m_{v, Br}$ but not for $m_{v, Fa}$, the value in column (8) is not the brightest magnitude, but whatever $V$-band photometry we had available. We have the necessary polarimetry and photometry data to compare the polarized flux at the epoch of maximum observed percent polarization ($P_m$) and the polarized flux when the object is at its observed brightest for 18 objects. We observe $P_m$ at the same time as the brightest emission for nine objects. The epochs of $P_m$ and brightest emission do not correspond for the other objects. The polarized flux was greater for two of these objects at the time of $m_{v, Br}$ despite a lower observed percent
polarization ($P$ at the epoch of $m_{v,Br} < P_m$). For the other seven objects the polarized flux was larger at the time of $P_m$ even though the corresponding $m_v$ is fainter than $m_{v,Br}$. The behavior of two specific objects is worth separate attention. MS 1221.8+2452 has displayed a great range in polarization while maintaining the same brightness. On two occasions this object had an $m_v$ of 17.3. The polarizations, however, were quite different, $11.86 \pm 0.61\%$ and $2.08 \pm 0.28\%$. 1E 1415.6+2557 had its largest output of polarized emission when it was at its faintest. We do not have a clear picture of what happens to these objects at low total and polarized fluxes, because it is not easy to obtain adequate data when these objects are faint and/or weakly polarized.

In general XSBLs are variable in total and polarized emission, but total flux increases are not necessarily accompanied by an increase in polarized flux.
4. Are XSBLs Really BL Lac Objects?

We have obtained a large amount of data on the polarizations and flux variations of our study sample of XSBLs and can use these data to examine the objects’ classifications as BL Lac objects. BL Lac objects must exhibit flux variations and produce variable polarized emission in addition to the spectroscopic restriction of having no strong emission lines. We now reevaluate the classification of each of the objects.

The usual dividing line for “significant” polarization or membership in the class of BL Lac objects, highly polarized quasars, or blazars is $P > 3\%$ (Impey & Tapia 1990; Kühn & Schmidt 1990). If we rigorously apply this threshold, several of the objects which were detected to be polarized would have to be excluded from our list of XSBLs. However, the main purpose of the polarization criterion of our BL Lac object definition is to confirm the synchrotron source contribution to the flux of the candidate BL Lac object. Since we have checked for interstellar polarization and in light of the low duty cycle of XSBLs (§ 2.2.2), we will retain the objects with low polarizations unless significant interstellar polarization was detected. Note that some researchers have chosen to drop the requirement that BL Lac candidates be significantly polarized, relying instead on the overall spectral energy distribution of the sources (e.g. Schacter et al. 1993). It remains to be determined if the objects selected in this manner have the same polarization and variability properties as the samples studied in this paper and paper III.

After applying our definition of a BL Lac object to our study sample, we are left with 27 confirmed BL Lac objects. We indicate in column (12) of Table 1 whether or not the object is a confirmed (C) BL Lac object. Of the 22 C-EMSS BL Lac objects we can only confirm the classification of 15. Of the remaining seven, one was not successfully observed for polarization. The other six objects failed to have detectable polarized emission despite repeated observations. Of the 12 EMSS candidate BL Lac objects, we have
detected polarized emission from three of the six observed objects (MS 2336.5+0517, MS 2342.7−1531, MS 2347.4+1924).

5. Discussion and Summary of Results

Our observations have produced the largest and most systematically compiled database on the polarization of XSBLs. Our polarimetry observations confirm that X-ray flux limited surveys find objects that meet the definition of being BL Lac objects since the majority (although not all) of the XSBL candidates possess intrinsically polarized and variable optical continua. Repeated observations of the candidate BL Lac objects that we have not extensively monitored should be continued. If we had used only the first epoch observations, only 35% of the sample would have been confirmed to be BL Lac objects.

While these objects are polarized, we have learned that their polarized emission has a low duty cycle, \( \sim 40\% \). Not only are they seldom highly polarized, but the maximum observed polarizations are only around 10%. These low values of percent polarization are not solely the consequence of dilution of the nonthermal component by the host galaxy starlight.

Some of the objects are observed to have strong frequency dependence in their percent polarization. In all such cases the percent polarization increased with increasing frequency. For many of the objects in our sample the observed FDP is consistent with a single synchrotron source in a host elliptical galaxy. However, there are examples, most notably H 2154−304 where dilution of the polarization by the host galaxy light can not explain the observed FDP. Frequency dependence of the position angle was rarely observed in our sample. Note that FD\( \theta \) can not be explained by a galactic dilution model.

There is no simple correlation observed between total and polarized flux, although
usually an observed maximum in percent polarization accompanies the maximum production of polarized flux.

The vast majority (85%) of the XSBLs have preferred angles for their optical polarization during the three year monitoring campaign. As we have previously discussed (Jannuzi 1990), this must reflect long term stability of the projected (on the plane of the sky) geometry of the region producing the polarized emission. If optical synchrotron emission is responsible for the production of the polarized emission (see Kartje & Königl 1991 for discussion of a accretion disk scattering model) and this radiation is produced by a jet of material with a relativistic bulk velocity, then we would expect objects viewed at significant angles to the relativistic jet to have preferred angles in contrast to objects viewed directly “down” the jet. We would also expect a greater incidence of detectable optical jets among the objects with preferred position angles. We note that recently only the second example of an optical jet in a BL Lac object was reported by Romanishin (1992) (The first being PKS 0521–36, Keel 1986; Macchetto et al. 1991). The object, 1E 1415.6+2557, is an XSBL and one of the objects we observe to have a preferred angle for its optical polarization. The position angle of the jet is 146°, more orthogonal than aligned with the mean position angle of the polarized optical emission (18°, see Table 2 and Figure 2). The remaining uncertainty on the viewing angle to the jet makes it difficult to uniquely determine the polarization mechanism. However, if synchrotron radiation is the mechanism (which is certainly consistent with the observed variability of the polarized flux), then the observed preferred angle for the polarization and the observed “jet” might be used to constrain models for the magnetic field distribution in the jet. If the generation of the optical and radio “jets” are closely related and have the same or general geometry we might also expect a greater incidence of extended and/or asymmetric radio emission from the objects with preferred angles.
We have confirmed the variability of many of the objects in our sample. We have not observed any examples of the large and rapid fluctuations typical of optically violent variable quasars or the well known radio selected BL Lac objects. The largest $V$-band variation (peak to peak during the period of monitoring) was only 1.18 magnitudes.

In paper III we compare the observed properties of XSBLs with those of other extragalactic objects which exhibit significant variable polarization. We will discuss further the derivation of the range of intrinsic physical properties of the class from the observed properties of BL Lac objects.

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Table 1 is a landscape table and is contained in a separate file.

Table 1:
Table 2 is a landscape table and is contained in a separate file.

Table 2:
Table 3 is a landscape table and is contained in a separate file.

Table 3:
REFERENCES

Abraham, R. 1991, MNRAS, 249, 742

Abraham, R. 1991, MNRAS, 252, 482

Allen, R. G., Smith, P. S., Angel, J. R. P., Miller, B. W., Anderson, S. F., & Margon, B. 1993, ApJ, 403, 610

Brissenden, R. J. V., Remillard, R. A., Tuohy, I. R., Schwartz, D. A., & Hertz, P. L. 1990, ApJ, 350, 578

Coleman, G. D., Wu, C., & Weedman, D. W., 1980, ApJS, 43, 393

Cruz-Gonzalez, I & Huchra, J. P. 1984, AJ, 89, 441

Fugmann, W., & Meisenheimer, K. 1988, A&AS, 76, 211

Gioia, I. M., et al. 1990, ApJS, 72, 567

Impey, C. D., & Tapia, S. 1990, ApJ, 354, 124

Jannuzi, B. T. 1990, Ph.D. thesis, University of Arizona

Jannuzi, B. T., Smith, P. S., & Elston, R. 1993, ApJS, 85, 265 (paper I)

Jannuzi, B. T., Elston, R. & Smith, P. S. 1994, in preparation (paper III)

Kartje, J. F., & Königl, A. 1991, ApJ, 375, 69

Keel, W. C. 1986, ApJ, 302, 296

Kennicutt, R. C. 1992, ApJS, 79, 255
Laruent-Muehleisen, S. A., Kollgaard, R. I., Moellenbrock, G. A., and Feigelson, E. D. 1993, AJ, in press

Kühr, H., & Schmidt G. D. 1990, AJ, 99, 1

Macchetto, F. et al. 1991, ApJ, 369, L55

Mathewson, D. S., & Ford, V. L. 1970, MmRAS74, 139

Moore, R. L., & Stockman, H. S. 1984, ApJ, 279, 465

Morris, S. L., Stocke, J. T., Gioia, I. M., Schild, R. E., Wolter, A., Maccacaro, T., and Ceca, R. D. 1991, ApJ, 380, 49

Perlman, E., and Stocke, J.T. 1993, ApJ, 406, 430

Romanishen, W. 1992, ApJ, 401, L65

Schachter, J. F., et al. 1993, ApJ, 412, 541

Schwartz, D. A., et al. 1989, in BL Lac Objects, ed. L. Maraschi, T. Maccacaro, & M.-H. Ulrich (Berlin: Springer-Verlag), 209

Smith, P. S., Hall, P. B., Allen, R. G., & Sitko, M. L. 1992, ApJ, 400, 115

Smith, P. S., Jannuzi, B. T., & Elston, R. 1991, ApJS, 77, 67

Smith, P. S., & Sitko, M. L., 1991, ApJ, 383, 580

Stocke, J. T. 1990, personal communication

Stocke, J. T., Liebert, J., Schmidt, G., Gioia, I. M., Maccacaro, T., Schild, R. E., Maccagni, D., & Arp, H. C. 1985, ApJ, 298, 619
Stocke, J. T., Morris, S. L., Gioia, I. M., Maccacaro, T., Schild, R. E., & Wolter, A. 1989, in BL Lac Objects, ed. L. Maraschi, T. Maccacaro, & M.-H. Ulrich (Berlin: Springer-Verlag), 242

Stocke, J. T., Morris, S. L., Gioia, I. M., Maccacaro, T., Schild, R. E., & Wolter, A. 1990, ApJ, 348, 141

Stocke, J. T., et al. 1991, ApJ, 76, 813

Ulrich, M.-H. 1989, in BL Lac Objects, ed. L. Maraschi, T. Maccacaro, & M.-H. Ulrich (Berlin: Springer-Verlag), 45

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FIGURE CAPTIONS

Fig. 1.—Light curves of the apparent $V$-band magnitude ($m_v$), white light (unfiltered) percent polarization ($P$), and polarization position angle ($\theta$) for six XSBLs. The bottom axis indicates the UT date of observation. The top axis is the Julian Day of the observation minus 2,447,000. The vertical lines centered on each data point indicate the one sigma uncertainties in the measurements. (a.) H 0323+022 and H 1219+305. (b.) MS 1221.8+2452 and MS 1402.3+0416. (c.) H 1652+398 and MS 2143.4+0704.

Fig. 2.—We have plotted all of our white light polarization observations for 15 of the objects in our sample. The normalized Stokes parameters (Q/I and U/I) are shown with one sigma uncertainties. The distance from the origin indicates the percentage of polarization. The angle from the x axis is equal to $2 \times \theta$ (where $\theta$ is the PA of the polarized emission). Note that the vast majority of objects have preferred angles for the polarization position angle.

Fig. 3.—In this figure we display the ratio of the observed polarization to the intrinsic percent polarization of the synchrotron source versus the log of the observed frequency for various combinations of power law nonthermal sources and an elliptical host galaxy at a redshift of 0.2. Three groups of plots are shown for 4000 Å break (rest frame) strengths of 5, 15 and 25%. Within each group the four curves correspond to different values of the power law index, $\alpha$, of the nonthermal component. The specific values shown are 0.7, 1.1, 1.5 and 1.9. This choice cover the bulk of the observed range of $\alpha$ for BL Lac objects. The unpolarized starlight of the elliptical host galaxy reduces or dilutes the percent polarization of the synchrotron source. The dilution is most pronounced at longer wavelengths where the intrinsically red spectral energy distribution of the host galaxy contributes more flux. Note that as the break strength decreases (i.e. the nonthermal component becomes a larger fraction of the total emission) the effects of dilution greatly decrease. See §2.4 for further discussion. The centers of the filter bands used in the multiband polarimetry are indicated.
with the letters $UBVRI$. 