THE ASTROPHYSICAL JOURNAL, 302:337–351, 1986 March 1

H0323+022: A NEW BL LACERTAE OBJECT WITH EXTREMELY RAPID VARIABILITY

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Received 1985 April 26; accepted 1985 August 27

ABSTRACT

H0323+022 is a highly variable X-ray source discovered in the *HEAO 1* all-sky survey coincident with a 16th mag stellar object. Optical nebulosity around the object strongly suggests that it is a BL Lac object. This paper presents an investigation of H0323+022 with a variety of radio, optical, and X-ray telescopes. It is a BL Lac object lying in a $\sim 17\frac{1}{2}$th mag galaxy, including: optical nebulosity extending $\sim 15''$ about the stellar object; optical polarization varying between 2% and 9%; photometric variations up to 1 mag; variable radio emission around 50 mJy with a flat, bent spectrum; a steep lineless optical continuum spectrum; and a steep variable X-ray spectrum. The overall electromagnetic spectrum is similar to other X-ray–discovered BL Lac objects. The distance is estimated from the optical nebulosity to be about 600 Mpc, implying a moderate luminosity of $L_{\rm bol} \approx 5 \times 10^{45}$ ergs s^{-1}.

The most unusual aspect of H0323+022 is its rapid variability with optical polarization changes in tens of minutes, a factor of $\gtrsim 3$ change in X-rays in less than 6 hr (*HEAO 1*), and a factor of $\gtrsim 3$ decline in X-rays within 30 s, which has high statistical significance. It appears to be one of the most rapidly variable active galactic nuclei known. The $\Delta t \approx 30$ s variation of $\Delta L \approx 1 \times 10^{45}$ ergs s^{-1} indicates that the X-rays come from a compact region $\sim 1 \times 10^{12}\delta$ cm in size, where δ is the unknown relativistic Doppler beaming factor of the X-ray emitting region. Modest δ, $\gtrsim 3$, are implied to avoid super-Eddington conditions. An important consequence of this small size is that the X-ray emitting region is not cospatial with the radio emitting region, which is $\gtrsim 10^{17}$ cm in size with $\delta \gtrsim 8$. The rapidly variable X-rays and polarized optical emission may be produced either in the intense environment of nonthermal particles and photons that is thought to surround an accreting magnetized rotating black hole, or in a thin shock in a relativistic jet.

Subject headings: BL Lacertae objects — polarization — radiation mechanisms — radio sources: variable — X-rays: sources

I. INTRODUCTION

Large amplitude variability over all regions of the electromagnetic spectrum is a fundamental property of BL Lac objects. The variations typically occur on time scales of weeks to months, slow compared to the rapid luminosity changes theoretically achievable by a highly efficient engine (Elliot and Shapiro 1974). Reports of variations on much shorter time scales from a few BL Lac objects stand out in light of this large body of data. OJ 287, perhaps the most rapidly variable extragalactic object known, has exhibited radio variations in 2 hr or less (Epstein *et al.* 1972; Valtaoja *et al.* 1985), low-amplitude photometric variations in tens of minutes (e.g., Kikuchi and Inoue 1984; Holmes *et al.* 1984; Carrasco, Dultzin-Hacyan, and Cruz-Gonzales 1985), 4% optical polarization fluctuations in ~ 25 minutes (Kulshrestha, Joshi, and Deshpande 1984), and, on one occasion, ± 1 mag variations at 1.2 μm on 30 s time scales (Wolstencroft, Gilmore, and Williams 1982). X-ray variations in BL Lac objects have been seen on time scales of hours, with a probable 500 s event in Mrk 501 (Agrawal, Singh, and Riegler 1983; Schwartz, Madejski, and Ku 1983) and a tentative 1 s event in PKS 2155−304 (Agrawal and Riegler 1979). We present here a new BL Lac object characterized by X-ray changes on 30 s time scales, optical polarization changes in tens of minutes, and *UBV* and radio variations in 24 hr. The X-ray variations, perhaps the most rapid seen in any active galactic nucleus, may provide important insights into the nature of the central engines in BL Lac objects.

The object in question is H0323+022, a high-latitude X-ray source discovered (Doxsey *et al.* 1983) in the all-sky survey of the *HEAO 1* satellite. Doxsey *et al.* presented X-ray data from two satellites, optical spectroscopy, and preliminary radio data on the source and outlined possible explanations for its "puzzling" properties. The X-ray source is coincident with a $V = 16.5$ stellar object with an infrared excess. It showed no emission lines and no absorption lines except that, on two of seven occasions, zero-redshift absorption lines characteristic of a G star were detected. The latter were probably due to erroneous observations of a nearby star (Margon and Jacoby 1984). The X-ray light curves revealed extreme variability, including factors of $\gtrsim 3$ on time scales of ≤ 6 hr (*HEAO* A-1 observations) and a single factor of $\gtrsim 11$ decline within 1 minute (*Einstein* IPC observations). A single radio observation gave 41 mJy at 4.9 GHz. These data were not readily reconciled. The radio, infrared excess, and featureless optical spectra suggested a BL Lac object, but the X-ray variations were orders of magnitude faster than any previously known. A Galactic X-ray binary model with a normal low-mass star and

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a compact companion was also considered, though the radio emission and absence of optical emission lines were not easily explained.

The options concerning the nature of H0323+022 were further constrained by the discovery of an asymmetrical optical nebulosity extending about 8″ from the stellar object by Margon and Jacoby (1984). It was consistent with a host galaxy of a BL Lac object 1000 ± 500 Mpc distant but could not be readily explained in a binary star model.

This paper presents the results of a multiband, multiepoch series of observations that demonstrate beyond reasonable doubt that H0323+022 is a remarkably variable BL Lac object. The optical nebulosity around the stellar object is confirmed, the stellar optical radiation is polarized, and the radio characteristics and the overall electromagnetic spectrum resemble those of other BL Lac objects. Variability is seen in all bands, including radio and broad-band optical variations in days, optical polarization changes on time scales of tens of minutes, and X-ray changes on time scales of ~30 s. H0323+022 is thus an active galactic nucleus with much of the observed emission emerging from a region $\lesssim 10^{12}$–10^{14} cm in size.

II. OBSERVATIONS AND RESULTS

a) Optical Imagery

H0323+022 was observed by two of us (P. A. W. and S. W.) on 1983 November 28 with an RCA CCD detector on the No. 1 0.9 m telescope at Kitt Peak National Observatory. Three 10 minute exposures through a *V* filter were obtained. The seeing FWHM was ~1″.5, and the plate scale was 0″.86 pixel^{-1}. Flat-fielding corrections were made following standard KPNO procedure, using an illuminated screen on the inside of the dome. Observations of four standard stars in the cluster NGC 2264 provided the magnitude calibration. The three images of H0323+022 were registered to a small fraction of a pixel and were averaged to obtain a single image. Further analysis was carried out with the Interactive Picture Processing System at Kitt Peak by one of us (W. R.) following procedures described in Romanishin *et al.* (1984) and Romanishin and Hintzen (in preparation).

The image of H0323+022 shows a basically symmetric nebulosity, although one quadrant centered at P.A. ≈ 240° contains additional structure extending about 8″ from the central source at a surface brightness of about 25 mag arcsec^{-2}. This is the feature described by Margon and Jacoby (1984) and is shown in their Figure 1. The main nebulosity has an axial ratio $b/a \approx 0.85$ and a major axis at P.A. ≈ 50°. The asymmetric portion of the nebulosity contains only a small fraction (<10%) of the total flux from the nebulosity. The present data cannot be used to ascertain the nature of the asymmetric portion of the nebula, but it could be a superposed (interacting?) companion to the main host galaxy. The quadrant containing the asymmetric portion of the nebulosity was ignored in the following analysis.

Figure 1 shows the azimuthally averaged intensity profile of H0323+022. The total *V* magnitude of the object, integrated to the limits of detectability (≈15″ radius), is 16.55 ± 0.05. Also shown in Figure 1 is the profile of the point spread function for this image, obtained by summing three stars in the same CCD frame. The analysis technique consists of comparison of the H0323+022 radial profile with galaxy models convolved with this point spread function. We find that H0323+022 can be

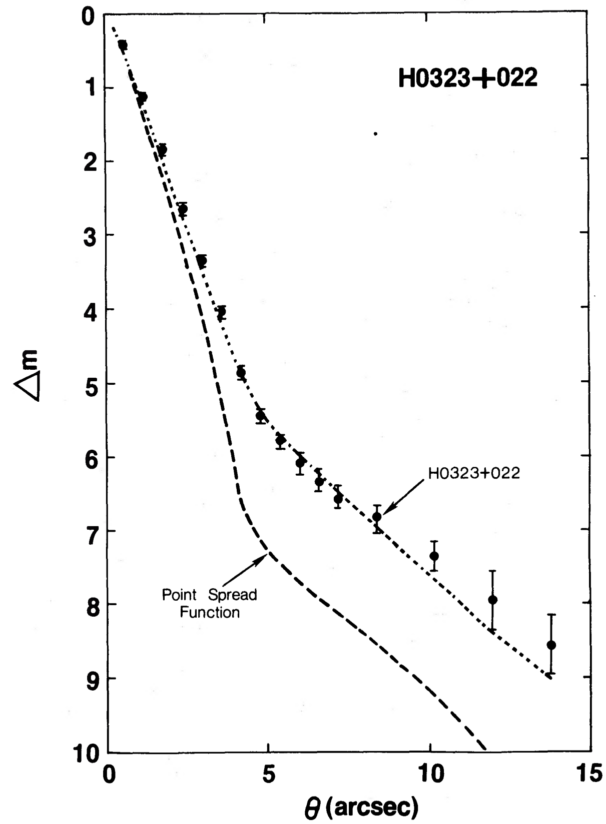

FIG. 1.—Radial profile of the CCD image of H0323+022. The circles with error bars show the azimuthally averaged surface brightness radial profile of H0323+022 from the CCD image, not including the quadrant containing the asymmetry. The long-dashed line is the profile of the point spread function obtained over the same range in position angle. The short-dashed line is the profile of the best-fit elliptical galaxy plus point source, after convolution with the point spread function.

readily understood as a seeing-degraded image of a point source in an elliptical galaxy (de Vaucouleurs $[r/r_e]^{1/4}$ profile), as has been found for other BL Lac objects (Weistrop *et al.* 1981; Hickson *et al.* 1982; Weistrop *et al.* 1985). Models consisting of a point source plus a spiral galaxy (exponential disk intensity profile) do not reproduce the profile very well, although they cannot be totally ruled out with the present data. The effective radius of the elliptical galaxy is $r_e = 1''.6 \pm 0''.6$, while the point-to-galaxy flux ratio $F_{\rm pt}/F_{\rm gal} = 1.3 \pm 0.4$. The magnitude of the nebulosity is thus estimated to be 17.5 ± 0.2.

Our measured apparent magnitude and effective radius can be used to estimate the redshift *z* of the H0323+022 host galaxy, assuming that it has a structure similar to a normal elliptical. We derived a graphical solution, shown in Figure 2, for *z* by comparing M_v derived from the observed magnitude of the nebulosity (*K*-corrections from Coleman, Wu, and Weedman 1980 are applied), with M_v derived from the relation

$$M_v = -1.72 \log r_e - 20.7 . \quad (1)$$

The slope of this relation is from Kormendy (1982), and the zero point was obtained from a least-squares fit with fixed slope to the M_v–log r_e points for 16 normal ellipticals in Kormendy (1977). We used $B-V = 0.9$ to convert from M_B to M_v and assumed Galactic absorption $A_v = 0.2$ csc *b*. $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.0$ were assumed throughout. The result

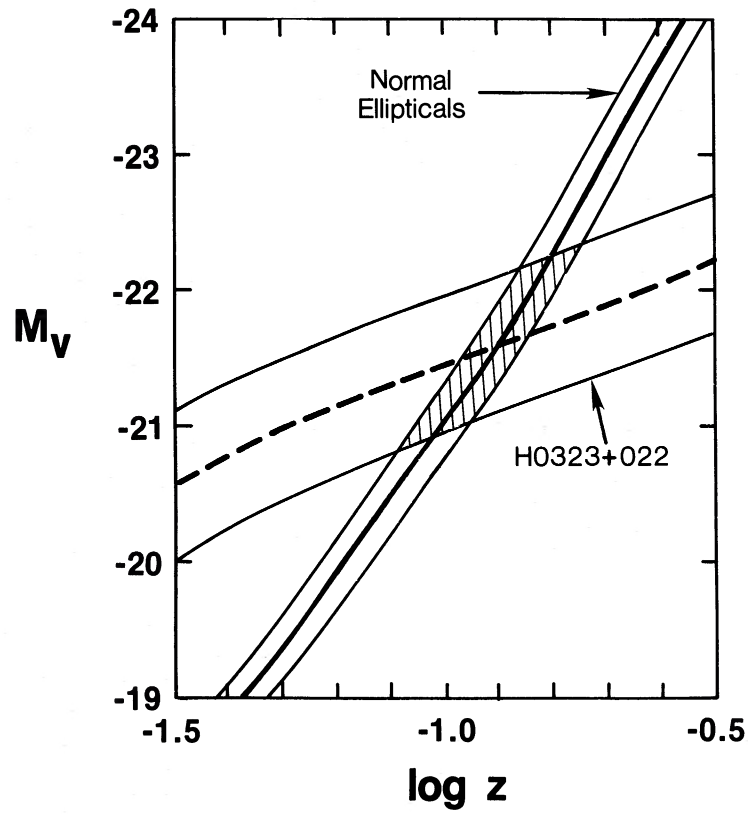

FIG. 2.—The solid line shows the M_v-z relation for normal elliptical galaxies, derived from data of Kormendy (1977, 1982), and the dashed line represents the M_v-z relation associated with the nebulosity of H0323+022. The hatched area shows the overlapping region and inferred estimate of $z = 0.13 \pm 0.05$.

of this method is a redshift estimate $z = 0.13 \pm 0.05$, with $M_v = -21.6 \pm 0.7$ for the host galaxy. The errors are based on an estimated uncertainty of ± 0.2 m in the nebulosity's apparent magnitude and a scatter of ± 0.5 m around the M_v–log r_e relation. We note that a different M–log r_e relation has been found by Davies *et al.* (1983), which gives a highly uncertain redshift estimate due to the similarity of slopes of the M_v–z lines. Because the Kormendy data are based on detailed surface photometry, we prefer the slope he derives.

We have checked this redshift estimate with two less sophisticated tests. Wyckoff, Wehinger, and Gehren (1981) and Gehren *et al.* (1984) provide data on the apparent R magnitudes, angular extents, and redshifts for the host galaxies of 29 quasars. A comparison with the magnitude and extent of the H0323+022 nebulosity, with appropriate color corrections, gives $0.1 \lesssim z \lesssim 0.2$. This estimate, of course, assumes that the host galaxies of quasars and H0323+022 are not extremely different.

For the remainder of this paper we will adopt a redshift of 0.15 and a distance of 600 Mpc (assuming $H_0 = 75$ km s^{-1} Mpc^{-1}) for H0323+022. This redshift is consistent with, though somewhat closer than, the estimate of 1000 ± 500 Mpc by Margon and Jacoby (1984). The host galaxy resembles an elliptical, ~ 1 mag fainter than the average first-rank elliptical in clusters, but also has an asymmetrical component ~ 25 kpc in extent. We encourage efforts to directly measure the redshift of the nebulosity, though it will be difficult, as no emission lines are present. The object 1′ east of H0323+022, as noted by Margon and Jacoby, is a resolved galaxy and may be a companion whose redshift will be easier to obtain.

b) *Optical Polarimetry*

Optical polarization measurements of H0323+022 were performed by one of us (S. T.) on seven nights between 1983 October and 1984 January with the 1.5 m telescope at the Cerro Tololo Inter-American Observatory and the 2.2 and 1.55 m telescopes of the University of Arizona Steward Observatory. The observations were made in a spectral band covering the region of 5000 Å to 9000 Å with the Minipol photopolarimeter (Frecker and Serkowski 1976). Table 1 gives the observation date, telescope, duration of observations, mean polarized fraction, and position angle for each night. A 5″ diameter circular aperture was used in all observations. Fits to the 12 ms instrumental cycle to obtain the polarized fraction and position angle were made every 120 s, except for December 7 when the integration time was reduced to 60 s. The uncertainty associated with each point is calculated from these fits. Sky polarization is monitored every 15–30 minutes and is subtracted from the data. This correction is about 1% of the total intensity of H0323+022 and is constant to within a few tenths of a percent. We also suspect that the polarization fraction is slightly diluted by the optical nebulosity discussed above (see Maza, Martin, and Angel 1978).

Table 1 shows that the broad-band optical emission of H0323+022 is polarized by 2%–9%, and that the polarization can change in both angle and intensity within 24 hr. This is most clearly seen between 1983 December 30 and 31, which differ by 3.4% ± 0.8% in polarization fraction and 73° ± 7° in polarization angle. The angle shift demonstrates that the change cannot be due to a variation in the unpolarized continuum. But of greater interest are the variations seen within two

TABLE 1

OPTICAL POLARIMETRY MEASUREMENTS

Date	Telescope	Duration (minutes)	Average Polarization	Polarization P.A.
1983 Oct 26	CTIO 1.5 m	3	4.8% ± 1.4%	164° ± 8°
1983 Oct 27	CTIO 1.5 m	3	4.3 ± 1.0	134 ± 7
1983 Oct 28	CTIO 1.5 m	17	2.2 ± 0.2	150 ± 3
1983 Dec 07	UAO 2.2 m	88	3.5 ± 0.3	19 ± 2
1983 Dec 30	UAO 1.55 m	10	5.9 ± 0.5	110 ± 2
1983 Dec 31	UAO 1.55 m	114	2.5 ± 0.6	37 ± 7
1984 Jan 1	UAO 1.55 m	54	a	70

[a] Highly variable between 2% and 9%.

of the longer scans, as shown in Figure 3. On 1984 January 1 the polarization fraction increased from 3% to 9% and fell again within 70 minutes. The χ^2 with respect to a constant level is 97 with 26 degrees of freedom, with a corresponding significance level of $P = 10^{-5}$. On 1983 December 31, a comparison of the first 70 minutes with the second 70 minutes shows a drop from 2.85% ± 0.20% to 2.05% ± 0.18%, with a significance level $P = 0.3\%$.

A further peculiarity was seen on several occasions on different telescopes. The derived uncertainties associated with individual 120 s polarization fractions are sometimes substantially higher than those obtained at other times and larger than expected from photon statistics. Though this conceivably could be produced by rapidly moving cirrus clouds, the effect was not seen in other sources observed on the same nights. Very rapid variations, on time scales shorter than 120 s, of polarization in H0323+022 are suggested. This possibility is being investigated further.

c) Optical Photometry

Short and intermediate time scale broad-band optical measurements were made on a number of occasions. The object

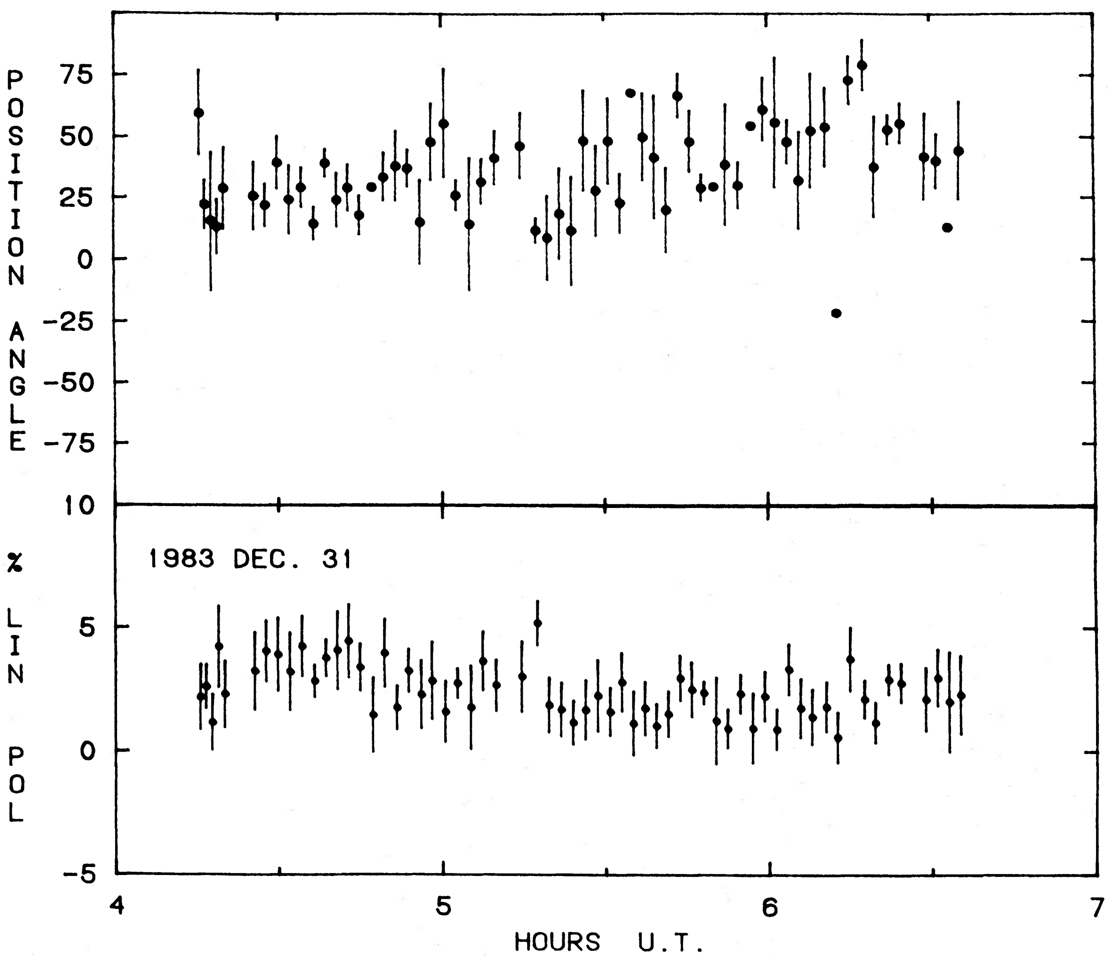

FIG. 3*a*

FIG. 3.—Short–time scale light curves of optical polarization fraction and position angle during (*a*) 1983 December 31 and (*b*) 1984 January 1 using the Minipol polarimeter on the University of Arizona 1.55 m telescope.

was monitored for a total of 11.9 hr on 1982 August 12–15 with the MIT scanning slit photometer (Franz 1967) at the McGraw-Hill 1.3 m telescope by two of us (J. M. and J. T.). With integration times of 5–10 minutes and a bandpass spanning 5000–9000 Å, no short–time scale source variations greater than the statistical 3%–5% RMS fluctuations were seen. A secular decrease of 0.135 ± 0.010 mag was observed to occur between the nights of August 13 and 14, and a decrease of 0.062 ± 0.009 mag was seen between August 14 and 15. This photometer measures the object, sky, and a standard star with a cycle time of ~ 10 s; we have high confidence that this result is free of systematic errors.

UBV photometry was carried out on six nights on 1982 October on the 0.9 and 1.0 m telescopes at the Cerro Tololo Inter-American Observatory by three of us (H. B., R. R., and B. E. S.). The $V = 12.81$ star 1'.1 south of H0323+022 (star S) was used as a standard; diaphragm apertures of 16" and 25" were used. The results are given in Table 2. Note the decrease in V-band brightness of ~ 0.4 mag from October 18 to 22, while the B and U band fluxes were relatively constant. The large excursion in the V band on October 16 is accompanied by a comparable flare in U but relative quiescence in the B band. Confirmation of such unusual color excursions should be a priority of further observations of this object.

In 1982 December, B, V, R, and I magnitudes were measured by two of us (J. M. and R. R.) one to three times a night on six consecutive nights with the MIT CCD MASCOT detector on the McGraw-Hill telescope. The instrument is described by Ricker *et al.* (1981). No changes within or between nights were seen. The mean values were $V = 16.08 \pm 0.01$, $B-V = +0.59 \pm 0.04$, $V-R = +0.46 \pm 0.02$, and $R-I = +0.52 \pm 0.03$. This corresponds to increasing flux densities toward longer wavelengths (see Fig. 4). The *JHKL* magnitudes reported by Doxsey *et al.* (1983), for a different epoch, indicate further increases up to at least the K band.

One of us (B. E. S.) has examined the point source and small extended source catalogs of the *Infrared Astronomical Satellite* (*IRAS*) for far-infrared emission from H0323+022. No source was found with the following upper limits: <0.3 Jy (12 μm band), <0.3 Jy (25 μm band), <0.5 Jy (60 μm band), and <1.1 Jy (100 μm band). These limits are at least an order of magnitude above an interpolation between the near-infrared and the radio flux densities.

Finally, in the course of carrying out the polarization measurements discussed in § II*b*, one of us (S. T.) routinely measured the 5000–9000 Å brightness of H0323+022 relative to star S. On 1983 October 26 and December 31 and 1984 January 1 the object was 3.7 mag fainter than star S, but on 1983 December 30 was only 2.4 mag fainter. It thus exhibited a 1.3 mag flare with a decay time ≤ 1 day. The December 30

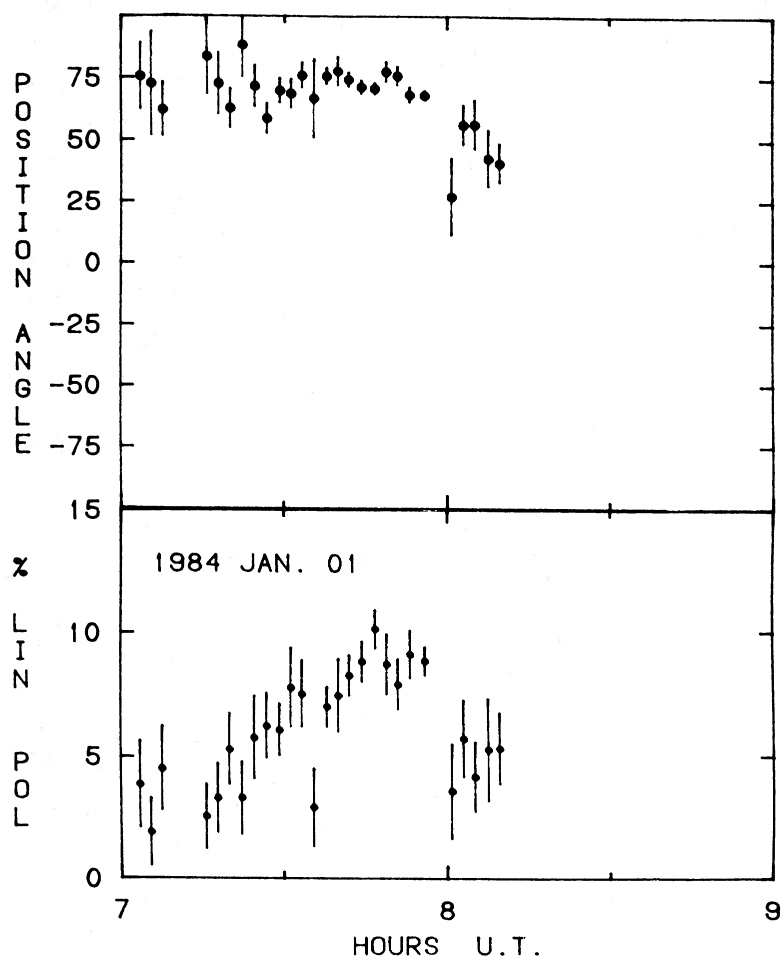

FIG. 3*b*

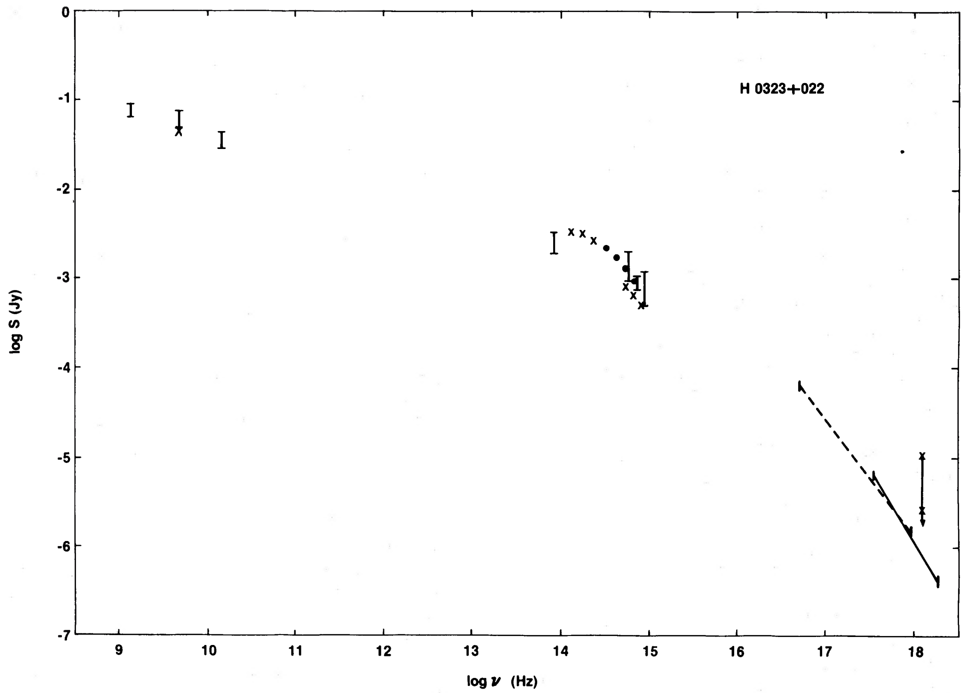

FIG. 4.—The composite electromagnetic spectrum of H0323+022. The crosses mark the data reported by Doxsey *et al.* (1983): a VLA 4.9 GHz measurement, *JHKL* photometry from the IRTF, *UBV* from the McGraw-Hill Observatory, and X-ray data showing the range of variations seen in the *HEAO 1* LASS experiment. The remaining data are from this study: the range of flux densities seen over several epochs at three frequencies at the VLA; *BVRI* photometry at a single epoch at McGraw-Hill (*filled circles*); the range of *UBV* photometry seen over several days at CTIO; the 0.2–4 keV X-ray spectrum from the *Einstein Observatory* IPC (*dashed line*); and the contemporaneous 1.5–8 keV MPC spectrum (*solid line*).

photometry was made under a clear sky; the rms deviations were 0.02 mag or less during the 5 and 17 minute observations of star S and H0323+022 respectively. The *V*-band magnitude was directly measured on 1984 January 1 to be 16.5.

The photometric properties of H0323+022 may be summarized as follows. Significant variations over periods of 1 or 2 days are seen with ranges of 0.8 mag (*V* band) and 1.3 mag (0.5–0.9 μm). The variations are not continuous, as indicated by the photometric stability during the 1982 December observations. No short–time scale variations were seen during the 1982 August observation, with a 2 σ upper limit of about 8% (0.08 mag) on time scales of 10 minutes.

d) Optical Spectroscopy

Doxsey *et al.* (1983) report uncalibrated spectra of H0323+022 obtained on seven different occasions, five showing a featureless continuum and two showing a zero-redshift G–F–type stellar spectrum. Credence was given to these latter observations because they were made by two different observers on different telescopes and nights. As argued by Margon and Jacoby (1984), we now feel these spectra must be put aside because (1) the observers do not have recorded evidence that the correct star was observed on these occasions, (2) both the bright star 1′ south and 1.′5 north of H0323+022 exhibit similar absorption spectra (Margon and Jacoby), (3) numerous other spectra of H0323+022 obtained by various observers fail to show the absorption line spectrum (Doxsey *et al.* 1983; Margon and Jacoby 1984; J. Huchra, private communication; G. Bothun and J. Patterson, private communication), and (4) the other compelling lines of evidence for the BL Lac nature of the object presented in this paper.

TABLE 2

UBV PHOTOMETRY, CTIO

Date (UT)	*V*	*B−V*	*U−B*
1982 Oct 14 0630	16.10 ± 0.02	0.59 ± 0.03	−0.57 ± 0.04
1982 Oct 16 0600	15.56 ± 0.04	0.96 ± 0.05	−1.04 ± 0.05
1982 Oct 18 0434	16.00 ± 0.10	0.79 ± 0.11	−0.61 ± 0.07
1982 Oct 20 0658	16.24 ± 0.04	0.52 ± 0.05	−0.62 ± 0.05
1982 Oct 21 0517	16.43 ± 0.04	0.48 ± 0.05	−0.50 ± 0.05
1982 Oct 22 0629	16.42 ± 0.04	0.41 ± 0.05	−0.57 ± 0.05

e) Radio Observations

H0323+022 was observed on nine occasions between 1982 September and 1984 March with the Very Large Array of the National Radio Astronomy Observatory[11] by three of us (E. D. F., B. G., and K. J.). An additional VLA observation in 1984 September was made by I. Gioia and T. Macaccaro (private communication). The instrument is described by Thompson *et al.* (1980). Exposures ranged from brief snapshots to several hours' continuous observation. The observation dates are separated by intervals ranging from 1 to more than 200 days. Table 3 gives the results of the monitoring, listing the date of observations, the array configuration, the source flux density (when observed) at 1.4, 4.9, and 14.9 GHz, and the resultant spectral indices ($S_\nu \propto \nu^{-\alpha}$) between adjacent bands. The original 1982 June observation reported by Doxsey *et al.* (1983) is also included. The flux densities were derived from small

[11] NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 3

VLA Radio Observations of H0323+022

Date	Array Configuration	Flux Density (mJy) 1.4 GHz	4.9 GHz	15 GHz	$\alpha_{1.4}^{4.9}$	$\alpha_{4.9}^{15}$
1982 Jun 21	A	...	41	...	...	...
1982 Sep 2	B	67	49	30	0.26	0.44
1983 Jan 17	D/C	88	59	...	0.33	...
1983 May 12	C	65	...	...	...	...
1983 May 14	C	66	...	...	...	...
1983 Dec 31	B	...	65	43	...	0.37
1984 Feb 8 0500 UT	B	73	61	37	0.15	0.45
1984 Feb 9 0500 UT	B	65	51	41	0.05	0.35
1984 Mar 17	C/B	85	75	29	0.10	0.85
1984 Mar 19	C/B	90	66	29	0.26	0.73
1984 Sep 8	D	71	64	57	0.09	0.10

CLEANed maps made with standard AIPS reduction programs and were calibrated to a local calibrator and the flux standard 3C 48. Nearby radio objects include an unresolved source 13′ east-southeast with 20 mJy at 1.4 GHz and an extended source 8′–12′ to the northeast with low surface brightness. The strong double source 3C 88 lies 30′ to the east of H0323+022 near the first null of the primary beam at 1.4 GHz. This makes it difficult to obtain reliable maps at 1.4 GHz in D and C array configurations. Calibration of antenna polarization characteristics was performed for the 1982 September 2 observation.

The flux densities in Table 3 have statistical rms uncertainties of about ± 0.5 mJy at 1.4 and 4.9 GHz and ± 1 mJy at 15 GHz. Systematic calibration uncertainties could range up to ± 1 mJy, or $\pm 5\%$ of the total flux densities. Spectral indices are accurate to about ± 0.1. Upper limits are given at 3 × rms. No extended emission was found down to 1% of the peak intensity, though the possibility of a weak and small ($\lesssim 5''$) extended component below this level is not excluded.

The data given in Table 3 indicate that H0323+022 varies by up to ~40% at all three frequencies on time scales of days and longer. Statistically significant variation was seen in 24 hr: a drop from 73 to 65 mJy at 1.4 GHz between 1984 February 8 and 9. The radio spectrum is variable but can in most epochs be characterized by a flat spectral index below 5 GHz ($0.1 \lesssim \alpha_{1.4}^{4.9} \lesssim 0.3$) and a steeper index above 5 GHz ($0.4 \lesssim \alpha_{4.9}^{15} \lesssim 0.8$). We find no correlation between intensity and spectral variations. Linear polarized flux was present on September 2 at 5% (1.4 GHz) and 6% (4.9 GHz) of the total intensity. No circular polarization was found.

The data were examined for short–time scale variations within each observation. In most cases, we can compare flux densities in two scans separated by 0.5–1 hr, but on 1983 January 17 and December 31 time series of 4–5 hr duration were available. No believable variations were found. Quantitative 3 σ limits of 5% at 4.9 GHz and 10% at 1.4 GHz for 10 minute time scale variability are derived from the 1983 January 17 observation. Very strong changes were seen within 30 minutes at 1.4 GHz on 1983 December 31 but appear to be due to loss of phase coherence in the array rather than true source variations. The cause of the effect is unknown but could be either local radio interference or ionospheric disturbances.

f) X-Ray Observations

Data from the imaging proportional counter (IPC) on board the *Einstein* (*HEAO 2*) satellite discussed by Doxsey *et al.* (1983) have been reprocessed and studied in detail by three of us (G. M., D. A. S., and E. D. F.) because of the great importance of the reported 1 minute time scale variation. Our findings concerning variability are described in the Appendix; they confirm and elaborate on the results of Doxsey *et al.* The results can be summarized as follows: (1) A secular decrease of ~30% is seen in a ~7 hr period. (2) The sudden decrease of intensity above 0.5 keV during one scan is confirmed. The statistical significance of the event is conservatively measured at $P \approx 10^{-13}$ and can be modeled as a disappearance of the flux, or at least factor of 3 drop in flux, on a time scale of ~30 s. (3) Numerous checks using the IPC background, the monitor proportional counter (MPC) detector, and various monitors of satellite performance and particle environment show no evidence of an instrumental origin for the event. The luminosity change corresponding to the observed 0.5–4 keV count rate change, based on the average IPC spectrum given below and an assumed distance of 600 Mpc, is 1.4×10^{45} ergs s^{-1}.

The X-ray spectrum in the IPC and MPC were measured during these observations. Both are well fitted by a power-law model. The MPC spectrum over the energy range 1.5–8 keV (frequency range $3.6–19.2 \times 10^{17}$ Hz) gives

$$S_\nu = 3.5(\nu/5 \times 10^{17}\ \text{Hz})^{-1.7}\ \mu\text{Jy}\ , \qquad (2)$$

with a $P = 5\%$ possible range in the spectral index of $1.5 \leq \alpha \leq 2.1$ (see Halpern 1982 for error analysis). The source is not detected above 8 keV. The absence of a low-energy cutoff implies a foreground column density $N_{\rm H} < 1 \times 10^{22}$ cm^{-2} assuming cosmic abundances. The mean IPC spectrum is fitted by

$$S_\nu = 3.0(\nu/5 \times 10^{17}\ \text{Hz})^{-1.35}\ \mu\text{Jy} \qquad (3)$$

over the energy range 0.2–4 keV ($0.5–9.6 \times 10^{17}$ Hz) with an index range of $1.13 \leq \alpha \leq 1.62$, including both systematic and statistical uncertainties (see Harnden *et al.* 1984 and Madejski 1985 for error analysis). The foreground column density is calculated to be $1.4^{+0.7}_{-0.5} \times 10^{21}$ cm^{-2} (a systematic uncertainty of $\log N_{\rm H} = 0.1$ is included), which is consistent with the value of $0.84 \pm 0.08 \times 10^{21}$ cm^{-2} derived from the Galactic H I column density derived from a recent 21 cm radio survey (Stark *et al.* 1985). We thus find that H0323+022, like other well-studied BL Lac objects (Worrall *et al.* 1981), has a steep X-ray spectrum ($\alpha \approx 1.5$) and negligible intrinsic absorption.

g) *Total Electromagnetic Spectrum*

The available data on the electromagnetic spectrum of H0323+022 (except for the far-infrared *IRAS* limits, which do not provide strong constraints), are plotted in Figure 4. Flux densities derived from optical/infrared magnitudes are based on the conversion factors of Cruz-Gonzalez and Huchra (1984). On a crude scale, the spectrum may be characterized by a flat power law between the radio and optical bands ($\alpha_r^o \approx 0.3$) and a steeper power law ($\alpha_o^x \approx 0.7$) at frequencies above $\sim 10^{14.5}$ Hz. But considerable spectral complexity and variability is seen within each band. Spectral indices within the radio vary between 0.1 and 0.7, with the index above 5 GHz consistently steeper than that below 5 GHz (Table 3). In the near-infrared the spectrum is still flat, with $\alpha_J^H \approx 0.06 \pm 0.18$ around 2 μm (Doxsey *et al.* 1983), but steepens sharply in the optical. The spectral flattening in the *K* and *L* bands has been seen in a number of other BL Lac objects, particularly those with $z \lesssim 0.2$ and including the X-ray discovered objects 1219+305 and 2155−304 (Cruz-Gonzalez and Huchra 1984; Sitko *et al.* 1983). On several occasions $\alpha \approx 1.2$–1.3 in the *UBVR* bands, suggesting this represents a "quiescent" spectrum. The unobserved ultraviolet must be relatively flat in order to match the observed soft X-ray flux densities. The X-ray spectrum then steepens again with $\alpha_X \approx 1.5$ or greater, as implied by the variable hard component seen in the IPC. This complex spectrum requires several "kinks" in the spectrum: a flat index in the radio/infrared regions, steep in the optical, flatter in the ultraviolet, and steeper again in the X-rays.

We have taken a simplified spectrum with $\alpha_r^o = 0.33$, $\alpha_o^x = 0.73$, and $\alpha_x = 1.35$ passing through the points plotted in Figure 4 to estimate the bolometric luminosity of H0323+022. We obtain $L_{\rm bol} \approx 5 \times 10^{45} D_{600}^2$ ergs s^{-1} over $10^9 \lesssim \nu \lesssim 10^{18}$ Hz, where $D_{600} = D/600$ Mpc is the distance estimated in § II*a*. The majority of this emission occurs in the far-UV range $10^{15} \lesssim \nu \lesssim 10^{17}$ Hz, as is true of most BL Lac objects.

h) *Summary of Observations*

H0323+022 was previously known to be a high-latitude variable X-ray source coincident with a stellar ~ 16 mag object and associated nebulosity (Doxsey *et al.* 1983; Margon and Jacoby 1984). The principal results of our multiband study can be summarized as follows: (1) The optical nebulosity consists of a $\sim 30''$ diameter symmetric component, successfully modeled as an elliptical galaxy at $z \approx 0.15$ ($D \approx 600$ Mpc), and a smaller asymmetrical component; (2) optical polarization is present and varies in both intensity (2%–9%) and position angle on sequential nights and on time scales of tens of minutes; (3) the optical spectrum of the stellar component shows no emission or absorption lines; (4) optical photometry in 1982 October showed a 0.8 mag rise and fall in 5 days, while photometry over several days in 1982 December showed fluxes constant to within a few percent; (5) radio continuum observations show an unresolved ~ 50 mJy source that varies at all centimetric frequencies by ~ 40% on time scales of days, with a flat but "broken" spectrum; (6) X-ray emission in the 1.5–3 keV band dropped by a factor of more than 3 in less than 30 s during one orbit of the *Einstein Observatory* and showed variations on time scales of hours during other *Einstein* and *HEAO 1* observations; and (7) the overall electromagnetic spectrum of H0323+022 consists of several power-law components becoming progressively steeper at higher frequencies.

III. COMPARISON WITH OTHER BL LAC OBJECTS

The previous section presented several independent lines of evidence that H0323+022 is, in fact, a BL Lac object. These include the optical "fuzz" or nebulosity, the red featureless optical spectrum, the photometric variability, a flat and changing radio spectrum, linear polarization of several percent in the optical and radio bands, and strong variable X-ray emission with a steep spectrum. Any two or three of these properties would suggest a BL Lac object; the coincidence of all dispels any reasonable doubt. We proceed here with a more detailed comparison of H0323+022 with other BL Lac objects.

a) *Spectrum, Polarization, and Luminosity*

The overall electromagnetic spectrum of H0323+022 is consistent with that seen in many of the ~ 25 well-studied BL Lac objects. Using the "qualitative description" code of Cruz-Gonzalez and Huchra (1984, Table 3), it has a "steep decreasing" radio spectrum, a "galaxy and power law" optical-infrared spectrum, and X-ray flux "above" the optical-infrared continuum, and does "not" have an overall single power law. Most BL Lac objects were discovered as radio sources and thus generally have proportionally stronger radio emission (larger α_r^o) and weaker X-ray emission (larger α_o^x) than the X-ray–discovered H0323+022. Two other X-ray–selected BL Lac objects have very similar spectra: 2A 1218+304 (with $\alpha_r^{\rm IR} \approx 0.3$, $\alpha_o \approx 1.6 \pm 0.9$, $\alpha_o^x \approx 0.9$; Ledden *et al.* 1981, and references therein) and PKS 2155−304 ($\alpha_o^{\rm IR} \approx 0.2$, $\alpha_o \approx 0.8$, $\alpha_o^x \approx 0.8$; Urry and Mushotzky 1982, and references therein). Thus, aside from this expected selection effect, H0323+022 has an overall spectrum typical of BL Lac objects.

Spectral indices within specific spectral regions are sometimes unusual but not unique. Radio indices as steep as $\alpha_r = 0.8$, seen in H0323+022 in 1984 March, are quite rare but have been reported in a few BL Lac objects (Weiler and Johnston 1980; Cruz-Gonzalez and Huchra 1984). The infrared colors $J-H = 0.67 \pm 0.06$ and $H-K = 0.53 + 0.06$ (Doxsey *et al.* 1983) lie among those BL Lacs with a strong galaxy component (Allen, Ward, and Hyland 1982). Steep *UBV* indices like those seen in 1982 October have been seen in other objects (Landau *et al.* 1983; Cruz-Gonzalez and Huchra 1984), and the $\alpha_x = 1.5$ is typical of BL Lac objects (Worrall *et al.* 1981). The optical polarization fraction of 2%–9% is modest compared to many BL Lac objects (Angel and Stockman 1980).

The estimated bolometric luminosity of H0323+022, $L_{\rm bol} \approx 5 \times 10^{45}$ ergs s^{-1}, is fairly typical of other nearby BL Lac objects, such as the X-ray discovered Mrk 421, Mrk 501, 1218+304, and PKS 0548−322 and BL Lac itself. It should be noted that these objects are $\sim 10^2$ times less luminous than the more distant "blazars" like OJ 287, AO 0235+164, 3C 66A, and B2 1308+326.

b) *Variability*

While the spectrum, polarization, and luminosity of H0323+022 are unexceptional, its rapid variability in various bands is extraordinary. The radio flux varied by 10% in 24 hr (1984 February 8–9), the optical continuum decreased by 14% in 24 hr (1982 August 13–14), the polarized optical component tripled and declined with 70 minutes (1984 January 1), the X-ray emission fell by a factor of 3 or more in 6 hr or less (1978 August 13; Doxsey *et al.* 1983) and by a factor of 3 or less in ~ 30 s (1981 March 1). The principal BL Lac object with comparable reported variations is OJ 287 (details given in § I), although other BL Lac objects have convincing X-ray varia-

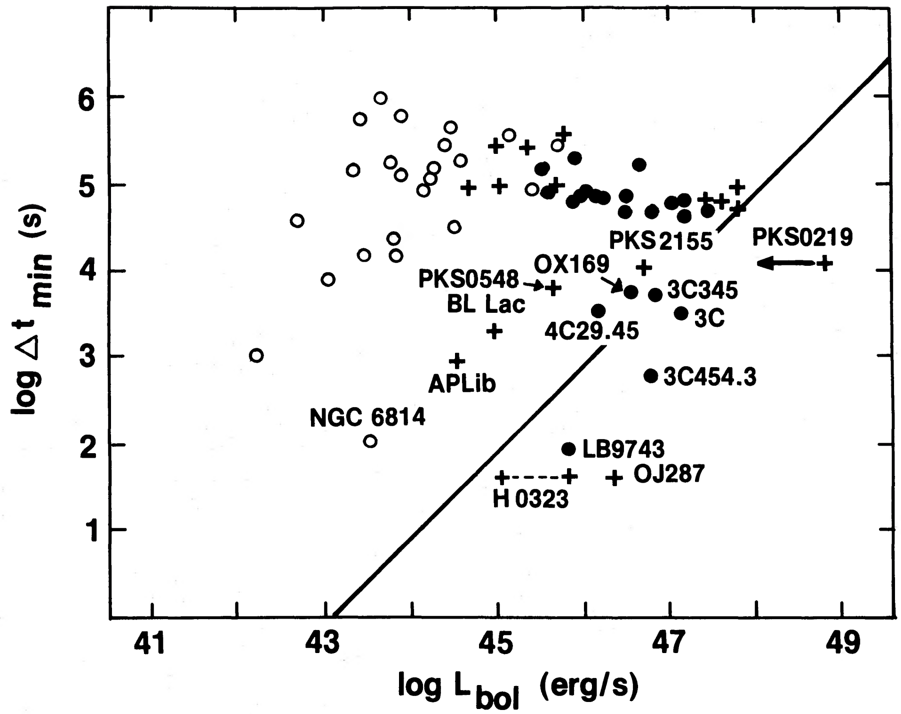

FIG. 5.—The ΔL-Δt_{min} diagram of variability in active galactic nuclei, adapted from Bassani, Dean, and Sembay (1983). See text and footnote 12 for details. Seyfert galaxies are noted by open circles, quasars by filled circles, and BL Lac objects by plusses. H0323+022 appears near the bottom, with the dashed line spanning the estimated variable X-ray and total bolometric luminosities. The diagonal line is the theoretical Elliot-Shapiro relation.

tions on time scales of hours. Only a few active galactic nuclei have reported variations in $\lesssim 10^3$ s. These include the low-luminosity Seyfert galaxy NGC 6814 (Tennant *et al.* 1981) and the radio-quiet quasars LB 9743 (Matilsky, Shrader, and Tananbaum 1982) in X-rays, and the radio-loud quasar 4C 29.45 (Grauer 1984) in the *B* band.

The variability of active galactic nuclei is frequently characterized by the ΔL-Δt_{min} diagram, where ΔL is the change in luminosity that occurs on the fastest observed time scale Δt_{min}. The most complete compilation of this diagram is that of Bassani, Dean, and Sembay (1983); we show their diagram with a few alterations and H0323+022 in Figure 5.[12] We caution that all locations in the diagram are quite uncertain. The Δt_{min} depends on how extensively an object has been observed on rapid time scales, and ΔL depends on the observed band and a large bolometric correction. H0323+022 is plotted both at $\Delta L = 1.4 \times 10^{45}$ ergs s^{-1}, which is the X-ray luminosity directly seen to vary, and at the bolometric luminosity 5×10^{45} ergs s^{-1} to be consistent with the other points plotted by Bassani *et al.* It is clear that H0323+022 varies extremely rapidly compared to other active galaxies but does not have a particularly high luminosity.

We are aware that the history of reported rapid variability in BL Lac objects is rather checkered. A considerable fraction of such findings have been retracted, criticized, not published, or at least not confirmed upon further study. BL Lac, for example, showed a 1.2 mag *V*-band variation in 23 minutes on one occasion (Weistrop 1973) but exhibited no more than 0.05 mag variations during extensive observations by Moore *et al.* (1982). OJ 287 showed remarkable ± 1 mag infrared variations in 30 s on one night but was stable on 11 other nights of observations by the same observers (Wolstencroft, Gilmore, and Williams 1982). In our own X-ray observations of H0323+022, the object showed only modest variations on time scales of several hours except for a single 5 minute period. These findings suggest that certain BL Lac objects are highly variable, but only sporadically. We can give several reasons why the 30 s H0323+022 X-ray variations are believable: the statistical significance is high ($P < 10^{-13}$); the imaging capability of the IPC and the redundant monitors on the satellite permit the simultaneous measurement of background and instrumental effects; variations on time scales of minutes and hours are independently demonstrated (polarized optical and *HEAO 1* X-ray emission). Furthermore, the object was not known to be a BL Lac object when the rapid variability was first reported, and thus expectations could not bias the data analysis. Coordinated multiband observations are in progress to search further for rapid variability in H0323+022 (H. Bradt, private communication).

IV. INTERPRETATION OF THE X-RAY VARIABILITY

a) General Considerations

Because the most remarkable aspect of H0323+022 is its apparent X-ray variability on time scales of tens of seconds, we

[12] The following changes are made to the ΔL-Δt_{min} diagram of Bassani *et al.* The value of Δt_{min} has been reduced to 4×10^3 s and 1×10^4 s for the BL Lac objects PKS 0548−322 and PKS 2155−304 respectively, based on the X-ray data of Agrawal, Singh, and Riegler (1983). We follow Bassani *et al.* in omitting the $\Delta t_{min} = 1$ s report of Agrawal and Riegler (1979). The "probable" 500 s X-ray event in Mrk 501 is also left out (Schwartz, Madejski, and Ku 1983). The $\Delta t_{min} = 1 \times 10^2$ s variation in 3C 66A has been increased to 1×10^5 s because the observers say the event is "only marginally significant and . . . suggestive" (Miller and McGimsey 1978). The 9×10^2 s time scale polarization variation in B21308+32 has been increased to 1×10^5 s due to a reanalysis of the data (Puschell, quoted in Angel and Stockman 1980). Three new objects have been added to the lower portion of the diagram: 4C 29.45, with $\Delta t \approx 2 \times 10^3$ s and $\Delta L \approx 8 \times 10^{45}$ ergs s^{-1} (Grauer 1984); PKS 0218−164, with $\Delta t \approx 1 \times 10^4$ s and unknown redshift or luminosity (Meisenheimer and Röser 1984); and H0323+022, with $\Delta t_{min} \approx 30$ s and $\Delta L \approx 1.4 \times 10^{45}$ (this paper).

concentrate on investigating its impact on physical models. The critical datum is that a luminosity decrease of $\Delta L \approx 1.4 \times 10^{45} D_{600}^2$ ergs s^{-1} of $\nu \approx 10^{18}$ Hz radiation occurred within a time $\Delta t \approx 30$ s. Two general, nearly "model-independent" interpretations of rapid variability in active galaxies can be applied.

First, Elliot and Shapiro (1974) considered the constraint on variations based on the Eddington limit, where the gravitational attraction of a compact mass is matched by radiation pressure on the accreting material. If the minimum time scale $\Delta t_{\min}$ of variations is set equal to the light travel time across a Schwarzschild radius, then the relation

$$\log \Delta L = 43.1 + \log \Delta t_{\min} \quad (4)$$

is obtained. It is plotted in Figure 5. For $\Delta L \approx 1.4 \times 10^{45}$ ergs s^{-1}, the minimum time scale is 110 s, which is $\sim$4 times the observed value. A maximally radiating compact object with a Schwarzschild radius crossing time of 30 s has $R_s \approx 1 \times 10^{12}$ cm, $M \approx 3 \times 10^6\ M_\odot$, and an Eddington limit $L_{\rm Edd} \approx 3 \times 10^{44}$ ergs s^{-1}.

Second, Fabian (1979) introduced a limit on the luminosity of an outburst arising from the Thompson opacity of the matter responsible for the emission. Assuming the luminosity is produced by mass conversion with an efficiency $\eta = (L\Delta t)/(Mc^2)$, the maximum luminosity permitted is

$$\log \Delta L = 41.3 + \log (\eta/0.1) + \log \Delta t_{\min} . \quad (5)$$

If $\Delta t \approx 30$ s and $\eta \lesssim 0.4$, then the peak luminosity should be $\Delta L \leq 2 \times 10^{43}$ ergs s^{-1} or $\gtrsim$70 times less than the observed change in H0323+022. This indicates that one or more of the assumptions underlying this calculation—spherical geometry, homogeneity within the region, isotropy of the emission, absence of relativistic bulk motions, and energy from mass conversion rather than (say) rotation energy—must be violated.

The apparent violation of equations (4) and (5) can be alleviated under a number of plausible conditions. Anisotropy of the radiation emerging from the funnel of a thick accretion disk can enhance the inferred luminosity 10^1–10^2 times above the Eddington limit if the observer lies close to the jet axis (Abramowicz and Nobili 1982). Relativistic bulk motion of the X-ray emitting region, even if the emission is intrinsically isotropic, would also have a major effect. If $\delta = (1 + v^2/c^2)^{1/2}/[1 - v/c(\cos\theta)]$ is the relativistic Doppler factor corresponding to motion with velocity v at an angle θ to the line of sight, then the rest frame luminosity can be substantially reduced, ΔL(emitted) $= \Delta L$(observed)δ^{-4}, and the rest frame variation time scale lengthened, Δt(emitted) $= \Delta t$(observed)δ. Thus, even equation (5) above could be satisfied with modest Doppler factors of $\delta \approx 3$. Such motions of the X-ray emitting region are plausibly present, since the radio emitting region must have $\delta \gtrsim 8$ (§ IV*b*).

We conclude that the X-ray variations in H0323+022 are moderately super-Eddington. A Doppler factor of $\delta \approx 3$ from a maximally radiating black hole with $M \approx 3 \times 10^6\ M_\odot$ could account for the variability. Since the intrinsic variability time scale varies only linearly with δ, it is difficult to escape the inference that the X-rays are being produced in an extremely small region, $R \approx 1 \times 10^{12}\delta$ cm, comparable to the Schwarzschild radius of a 10^6–$10^7\ M_\odot$ black hole.

b) Synchrotron Self-Compton Model

The synchrotron self-Compton (SSC) model, in which X-rays are produced by inverse Compton scattering of radio photons by the synchrotron-producing electrons, has been extensively applied to explain the X-ray emission in BL Lac objects (e.g., Marscher and Broderick 1981; Urry and Mushotzky 1982; Madejski and Schwartz 1983; Unwin *et al.* 1983; Worrall *et al.* 1984; Bregman *et al.* 1984; and many references in these papers and the review by Cohen 1985). The model is fully determined by the flux, spectrum, size, and motion of the radio-emitting region. The general result for BL Lac objects is that the predicted levels of SSC X-rays greatly exceeds the observed levels unless the radio emission is beamed toward us with Doppler factor at least $2 \lesssim \delta \lesssim 20$. This conclusion supports the evidence for relativistic beaming from the apparent superluminal proper motions seen in VLBI maps of compact radio sources. We apply here the SSC calculations to H0323+022 but follow with a strong argument that the observed X-rays are *not* produced according to the simple SSC model.

Since no VLBI measurements of H0323+022 have been made, we estimate the size of the radio emitting region from the radio variability. Table 3 shows a 20% variation in 1 day (1984 February 8–9) and $\sim$40% variation in 36 days (1984 February 9–March 17) at 4.9 GHz. Though these data are insufficient for a clear determination, we tentatively adopt a minimum variability time scale $\Delta t \approx 5$ days for the component that dominates at 5 GHz. The inferred angular size is then

$$\phi \approx 2c\Delta t\delta(1 + z)/D = 3 \times 10^{-3}(\Delta t/5d)D_{600}^{-1}\,\delta \text{ mas} . \quad (6)$$

Using the SSC formalism of Jones, O'Dell, and Stein (1974), we derive the following expression for the self-Compton flux density $S_\nu^{\rm sC}$ at energy E_x (in keV):

$$S_\nu^{\rm sC} = 4.14 \times 10^{-6}(3.66 \times 10^{-4})^\alpha e_{\alpha 0}\, i_{\alpha 0}^{-2\alpha-2} \ln(\nu_b/\nu_A) \times \phi^{-4\alpha-6}\nu_A^{-3\alpha-5}S_A^{2\alpha+4}[(1+Z)/\delta]^{2\alpha+4}E_x^{-\alpha} \text{ Jy} , \quad (7)$$

where α is the spectral index of the optically thin synchrotron radiation, $e_{\alpha 0}$ and $i_{\alpha 0}$ are functions of α tabulated by Jones *et al.*, ν_A is the turnover frequency in GHz, ν_b is the break frequency in GHz (where the synchrotron spectrum steepens), ϕ is the angular size in millarcseconds given in equation (6) above, S_A is the flux density in Jy at the turnover frequency, z is the redshift, and δ is the kinematic Doppler factor defined earlier. (This equation differs slightly from that given by Marscher 1983, in using a consistent definition of the turnover frequency and flux density; see Urry 1984 for details.) The self-Compton flux density $S_\nu^{\rm sC}$ then lies in the energy range $E_{\min}$–$E_{\max}$, where (see Urry 1984)

$$E_{\min} = 8.4 \times 10^{-4} i_{\alpha 0}^{-2}\phi^{-4}\nu_A^{-3}S_A^2[(1+Z)/\delta]^3 \text{ keV} \quad (8a)$$

and

$$E_{\max} = 0.44(\nu_b/\nu_A)^2 E_{\min} . \quad (8b)$$

Applying this model to the 5 GHz radio component of H0323+022, we have $\nu_A = 5$ and $S_A = 0.055$. The ratio ν_b/ν_A is assumed to be $\sim$100 and the radio spectral index is assumed to be $\alpha = 0.5$; the calculation is fairly insensitive to these quantities. Solving equation (7) under the hypothesis that the observed X-ray flux density ($S_\nu^{\rm sC} = 8 \times 10^{-6}$ at $E_x = 1$) arises in the variable 5 GHz radio component gives a Doppler factor $\delta \approx 7$. Equations (8a) and (8b) then give the consistent result that the inverse Compton–scattered photons lie in the energy range 0.03–>100 keV. A similar calculation for the 1 GHz component, which, because it is seen to vary by 10% in 1 day, is assigned $\Delta t \approx 10$ days, gives $\delta \approx 8.5$. These values are only approximate as the radio parameters Δt, ν_A, and α are only crudely determined by the data. We conclude that a moderate beaming factor, $\delta \gtrsim 8$, in the radio emitting region is required to insure that the SSC X-ray emission does not exceed the observed level.

The X-ray variability on time scales as much as 10^4 shorter than the radio variability time scale, however, virtually precludes the possibility that the observed X-rays come from the entire radio emitting region (see Cohen 1985; Cohen and Unwin 1984). If all the observed radio flux were to come from the X-ray emitting region that varies with $\Delta t \approx 30$ s, its brightness temperature would be (Marscher *et al.* 1979)

$$T_b \approx 10^{23}(S_A/0.055 \text{ Jy})(\nu_A/5 \text{ GHz})^{-2} D_{600}^2 (\Delta t/30 \text{ s})^{-2} \delta^{-2} \text{ K} , \quad (9)$$

which is far in excess of the $T_b \approx 10^{12}$ K "Compton catastrophe" limit. An enormous Doppler factor of order $\delta \gtrsim 5 \times 10^3$ would be needed to avoid the Compton catastrophe. A more reasonable interpretation, consistent with other BL Lac objects, would be that the radio emission comes from a larger region with $R \approx c(\Delta t/5 \text{ days})\delta \approx 10^{17}$ cm, with a Doppler factor $\delta \gtrsim 8$ derived above. It would then be larger than, either embedding or spatially distinct from, the rapidly variable X-ray emitting region, which is $R \approx 10^{12}\delta$ cm in size. The simplest SSC model that associates the observed radio and X-ray fluxes in a single region cannot apply.

V. DISCUSSION

Although we have presented a wide range of data concerning H0323+022, its most salient features might be summarized by the following three statements:

i) H0323+022 is a fairly typical BL Lac object of moderate luminosity ($L_{\text{bol}} \approx 5 \times 10^{45}$ ergs s^{-1}) in its overall electromagnetic spectrum, polarization, and host galaxy. It joins several other BL Lac objects that have been discovered in X-ray, rather than radio, sky surveys.

ii) It exhibits sporadic variability on time scales of 10^5–10^7 s in many portions of the electromagnetic spectrum, as is frequently seen in BL Lac objects. The radio variations in $\Delta t \approx 5$ days implies relativistic bulk motion with $\delta \gtrsim 8$ in a region 10^{17} cm in size.

iii) Variations on time scales of 10^1 s are seen in hard X-rays and of 10^3 s in polarized optical emission. These spectral components must be generated in regions 10^{12}–$10^{14}\delta$ cm in size. The only previous reports of such rapid variations in a BL Lac object concern OJ 287.

The rapid X-ray variations, which we argue in the Appendix are truly convincing, suggest that these components of the spectrum may be generated very close to the Schwarzschild radius of an efficient central engine. Relativistic bulk motion with $\delta \gtrsim 3$ is quite possibly present in the X-ray emitting region, since the 30 s variation time scale exceeds the Elliot-Shapiro limit for a stationary, isotropic emitter (§ IV*a*). An application of Compton cooling shows that the observed radio emission must be generated in a region orders of magnitude larger than the X-ray emitting region (§ IV*b*).[13] For H0323+022, as in many other BL Lac objects, the synchrotron cooling time is an order of magnitude longer than the Compton cooling times. Therefore, the synchrotron self-Compton model commonly applied to explain BL Lac spectra, which assumes the radio and X-ray emitting regions are the same size, is internally inconsistent for these objects.

Having decoupled the spatial scales of the observed radio and X-ray emission, theoretical models of the electromagnetic spectrum as a whole have many unconstrained free parameters. In particular, it may be impossible to obtain clear characterization of physical properties and processes occurring in the most compact X-ray generating regions of the source. For example, the X-rays could be generated by the self-Compton process in compact knots or shocks. These structures could emit very little ($S_\nu \ll 1$ mJy) radio flux and still undergo Compton catastrophe on a time scale of 30 s. The average spectral index of the X-ray emission, $\alpha \approx 1.5$, is much steeper than the normal $\alpha \approx 0.7$ optically thin radio synchrotron spectrum. This is a drawback of models that explain the observed X-rays as Compton emission alone. The fact that the soft ($E < 0.5$ keV) X-rays did not turn off in 30 s as the hard X-rays did suggests that more than one X-ray component may be present.

More likely, the X-rays are due to synchrotron emission from extreme relativistic particles injected in a variable fashion. With the observed X-ray spectral index, an electron population of the form $N(\gamma) = N_0 \gamma^{-4}$ is needed in a simple synchrotron model (e.g., Tucker 1975). However, it is difficult to produce the observed X-ray luminosity with electrons having synchrotron loss times of order $\Delta t \approx 30$ s. A more plausible scenario is one in which the rapid intensity variations are produced by relativistic kinematic effects. For example, a relativistic jet pointing very close to the line of sight need change direction only slightly to make a large and rapid apparent luminosity change.

There are two plausible locations for the X-ray emitting region. First, as suggested by the general calculations in § IV*a*, it may be in close proximity to a massive black hole. The immediate vicinity of a rotating black hole, particularly if magnetic fields and a thick disk are present, is likely to be a complex environment of energetic particles, photons, and fields (e.g., Phinney 1983; Blandford 1984; Rees 1984). Production of energetic electrons or plasmas that radiate high-frequency synchrotron radiation, after beaming directions, or are rapidly Comptonized on time scales of 10^1–10^3 s seems feasible in this environment. If the variability time scales reflect the distances of the emitting regions from the central engine, then X-rays and optical polarization are generated close to the Schwarzschild radius (10^{12}–$10^{14}\delta$ cm), most of the optical and radio emission is generated further out (10^{16}–$10^{18}\delta$ cm), and bulk relativistic motions are present in both regions. Models of the radiation from rotating magnetized black holes are not yet available, but they should account for a "kinked" power law ($\alpha_r^o \approx 0.3$, $\alpha_o \approx 1.2$, $\alpha_o^x \approx 0.7$, $\alpha_x \approx 1.7$) spectrum with $L_{\text{bol}} \approx 5 \times 10^{45}$ ergs s^{-1} emerging from the entire source.

The second possible location of the X-ray emitting material is in a relativistic jet (Königl 1981; Reynolds 1982). The rapid variations seen in H0323+022 could be due to changes in the particle injection rate, magnetic field strength, or jet orientation or velocity in the region where the jet becomes optically thin to X-rays. The passage of shocks through a relativistic jet, in particular, has been proposed to explain variations of radio intensity, polarization, and structure in compact radio sources (Marscher and Gear 1985, and references therein). Marscher and Gear have emphasized that extremely rapid variations can in principle be seen far out in a relativistic jet if a strong planar shock is viewed head on. In their example, the submillimeter

[13] It is interesting to contrast this finding with the study of the BL Lac object 0735+178 by Bregman *et al.* (1984). They deduce from variability time scales that the X-ray and radio regions are cospatial and large (10^{18}–10^{20} cm), while the optical emission region is distinct and smaller (10^{16} cm).

emission of 3C 273 could vary in $\sim 10^5$ s even though the emitting region is $\sim 10^{19}$ cm from the core. In H0323+022, the X-ray variation requires that $\sim 10^{45}\delta^{-4}$ ergs s^{-1} (in the local frame) be produced in a shocked region with a depth along the line of sight of order $10^{12}\delta$ cm. As mentioned above, the steep X-ray spectral index implies that the dominant losses are synchrotron rather than inverse Compton.

In summary, we have an active galactic nucleus that in some ways is typical of its class (nearby BL Lac objects) but in one respect—its rapid X-ray and optical polarization variability—is quite remarkable. The explanation for this is probably that H0323+022 possesses a BL Lac characteristic in the extreme. It may have a relativistic jet with an unusually high bulk Doppler factor, or one that is unusually inhomogeneous. The geometry of the inner region may be such that the black hole itself is unusually "naked," allowing us to see photons produced very close to the Schwarszchild radius. The result is one of the few objects in the sky whose apparent luminosity variations violate the Eddington limit. Elucidation of the underlying mechanisms and models for H0323+022 will require further observations, particularly VLBI mapping of the core and simultaneous temporal studies at several wavebands.

Note added in manuscript 1985 July.—Filippenko *et al.* (1985) have reported a clear absorption line spectrum in the nebulosity around H0323+022. A redshift of 0.147 ± 0.001 is obtained, consistent with our estimate of $z \approx 0.15$.

We would like to thank G. Bothun, J. Huchra, and J. Patterson for communicating unpublished spectroscopic data; I. Gioia and T. Maccacaro for communicating unpublished radio data; B. Clark and the VLA staff for efficient scheduling and data reduction; and A. Brown and J. Linsky for generously trading their VLA time to permit simultaneous observations. We appreciate stimulating conversations and correspondence with K. P. Singh and a referee, A. P. Marscher. The facilities used in this study include the Kitt Peak National Observatory and Cerro Tololo Inter-American Observatory, operated by Aura, Inc., under contract with the National Science Foundation; the National Radio Astronomy Observatory, operated by Associated Universities, Inc., under contract with the National Science Foundation; and the McGraw-Hill Observatory, operated jointly by the University of Michigan, Dartmouth College, and the Massachusetts Institute of Technology. Funds supporting this study include NASA contracts NAS 8-27972 and NAS 8-20543; NASA grant NAG-8-494; NSF grants AST 81-15557 and AST 81-20261; and an NSF Presidential Young Investigator Award (AST 83-51447).

APPENDIX

TEMPORAL ANALYSIS OF THE *EINSTEIN* X-RAY OBSERVATIONS

H0323+022 was observed for 9672 s (2.7 hr) over a period of 9.5 hr on 1981 February 19 with the imaging proportional counter (IPC) on board the *Einstein X-Ray Observatory*. The satellite is described by Giacconi *et al.* (1979), and the detector is discussed in detail by Harnden *et al.* (1984). The data are the same as those reported by Doxsey *et al.* (1983), except that we use the "Rev. 1" reprocessing that applies stringent screening of instrumental effects and satellite aspect solutions. It also incorporates mapping of the detector gain variations and thus should give more reliable spectral results. The monitor proportional counter (MPC), which is a nonimaging instrument coaligned with the telescope axis, is less sensitive that the imaging detector but also provides useful data for H0323+022 during this period.

a) Long-Term (10^4 s) *Variations*

The IPC and MPC data are readily divided into six segments, each corresponding to a spacecraft orbit. Table 4 summarizes each segment, giving the start time and duration of good data relative to 1433 UT on 1981 February 19: the net counts and count rate seen within a 3′ radius circle around the source between 0.2 and 4.0 keV (background subtracted), and the best-fit power-law spectrum and corresponding 0.2–4.0 keV flux and 1 keV flux density. Errors associated with the count rates are Poisson uncertainties, and those associated with the spectral parameters are approximate 90% confidence levels for two parameters estimated simultaneously ($\chi^2_{\rm min} + 4.6$; see Avni 1976).

This table indicates that the X-ray flux of H0323+022 decreases by 30% in the course of ~ 7 hr. A simple χ^2 test of the hypothesis of a constant count rate based solely on Poisson uncertainties gives $\chi^2 = 80$ for 5 degrees of freedom, with a significance level of $P \approx 10^{-13}$. The principal systematic uncertainty is probably due to the spatial gain variations in the IPC. Madejski (1985) estimates that the systematic error in the broad-band flux for a source with $\alpha = 1.0$ and $\log N_{\rm H} = 21.0$ is approximately 5%. If this systematic uncertainty is added to the Poisson uncertainty (cf. Schwartz, Madejski, and Ku 1983), the resultant $\chi^2 = 25$ with 5 degrees of

TABLE 4

IPC X-RAY SCANS OF H0323+022

START TIME (s)	IPC LIVE TIME (s)	TOTAL SOURCE COUNTS	COUNT RATE (counts s^{-1})	SPECTRAL PARAMETERS			
				α	$\log N_{\rm H}$ (cm^{-2})	F_x(0.2–4.0 keV) (10^{-11} ergs s^{-1} cm^{-2})	S_x(1 keV) (μJy)
2212......	1846.5	1896 ± 44	1.03 ± 0.02	1.3 ± 0.5	21.0 ± 0.4	3.2	6.1
7864......	1853.3	1810 ± 43	0.98 ± 0.02	1.4 ± 0.5	21.1 ± 0.3	3.0	5.9
13662......	1831.8	1826 ± 43	1.00 ± 0.02	1.6 ± 0.8	21.4 ± 0.3	3.0	6.4
19046......	1892.1	1699 ± 42	0.90 ± 0.02	1.7 ± 0.7	21.2 ± 0.4	2.7	5.8
24617......	986.1	745 ± 28	0.76 ± 0.03	1.5 ± 1.2	21.3 ± 0.6	2.3	4.8
30474......	902.0	747 ± 28	0.83 ± 0.03	1.6 ± 1.1	21.3 ± 0.6	2.5	5.4

freedom at a significance level $P \approx 1 \times 10^{-4}$. There is no evidence that a spectral change accompanied the drop in intensity. We conclude that "long-term" IPC variations of $\sim 30\%$ amplitude exist on a time scale of $\sim 3 \times 10^4$ s.

b) The Rapid Event (10^1–10^2 s)

When individual orbits of IPC data are examined for variability on shorter time scales with respect to their local mean intensities, two segments show evidence of variability. In 100 s bins, the first orbit shows $\chi^2 = 50$ with 20 degrees of freedom ($P \approx 2 \times 10^{-4}$), and the fifth orbit shows $\chi^2 = 64$ with 10 degrees of freedom ($P = 6 \times 10^{-10}$). The variation in the latter orbit is very dramatic in the high-energy channels. Figure 6 shows the arrival time of each count in the IPC pulse invariant bins 7–21 (energy range 0.5–4 keV) for the variable fifth orbit. We apply two bin-free statistical tests that evaluate the significance level at which the arrival times are not consistent with a constant arrival rate. One test, the Kolmogorov-Smirnov statistic, measures the maximum deviation between the observed and expected integral distribution of arrival times while the second, the Smirnov–Cramer–Von Mises statistic, measures the average square difference between the two distributions (Eadie *et al.* 1971, pp. 268–271). These tests, which make no assumption regarding the time scale or nature of temporal anomaly, give significance levels of order $P \approx 10^{-13}$. The source behavior can be characterized by a constant count rate of 0.76 counts s^{-1} for the first 13 minutes of the scan (times 24,615 s–25,381 s), followed by more than one minute of *zero* count rate (25,381 s–25,449 s), followed by 3 minutes of variable flux averaging 0.4 counts s^{-1} (25,449 s–25,639 s).

During this scan the soft X-ray flux from H0323+022, measured in the IPC pulse invariant bins 1–6 (0.15–0.5 keV), was approximately constant. A Kolmogorov-Smirnov test gives a significance level of $P \approx 2\%$ for source variability, which is due to a moderate rise in flux around times 24,800–25,000 s. There is no deviation from the average soft count rate of 0.16 counts s^{-1} during the rapid changes seen in the hard X-ray channels.

Interpretation of the rapid 0.5–4 keV flux drop requires knowing the "time scale" of variation. Both binned and unbinned procedures can be utilized. We can estimate the time passed for the observed count rate to differ significantly from the "expected" rate of 0.76 counts s^{-1} that dominates the scan shown in Figure 6. At this rate, 12 counts should arrive every 16 s, yet zero counts are seen during the 16 s between 25,382 and 25,397 s. The Poisson probability of this occurring in a particular 16 s bin is $P \approx 5 \times 10^{-8}$. Since there are 64 16 s bins in the scan, the net chance of random occurrence is $P \approx 0.03\%$, or better than the 3 σ limit of a Gaussian distribution. An unbinned estimate can be calculated by finding that the distance between the observed integral count distribution and an assumed constant rate of 0.76 counts s^{-1} is significant at the $P = 1\%$ level using the Kolmogorov-Smirnov test about 55 s after the count rate appears to decline. This estimate is conservative due to the long period of constant flux; if the scan had started at 25,200 s rather than 24,615 s, the corresponding time scale of variation at the $P = 1\%$ level would be 40 s. Considering that the binned Poisson test gives significant variation in 16 s and an unbinned Kolmogorov-Smirnov test gives

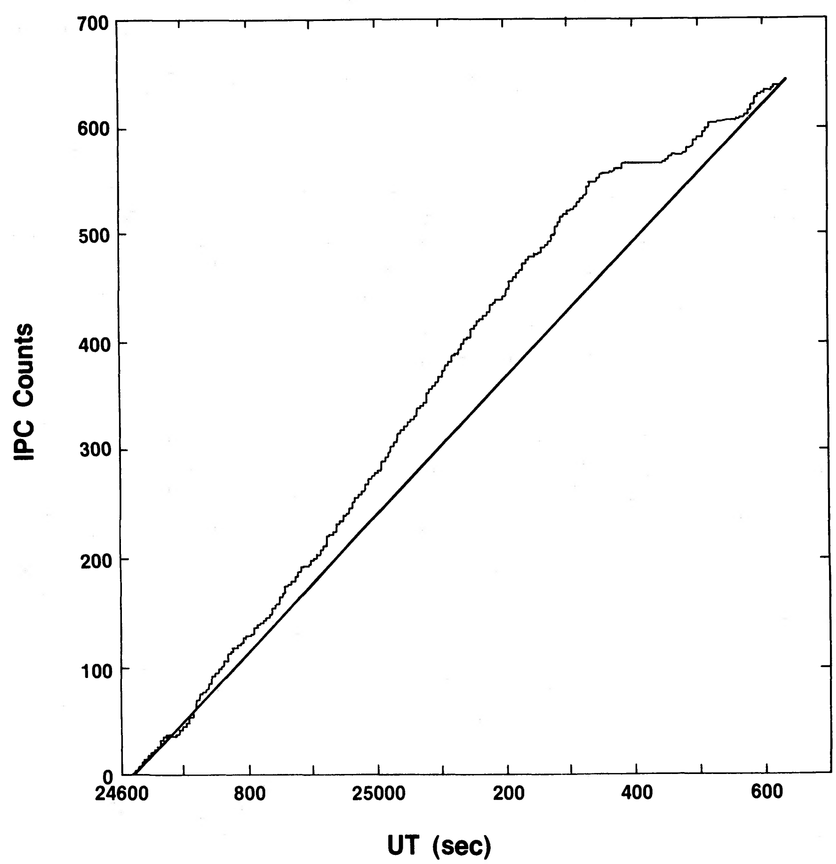

FIG. 6.—The integral distribution of 0.5–4 keV IPC count arrival times for H0323+022 during the fifth orbit of the *Einstein* satellite. Note the period around 25,400 s when no counts are seen. The straight line shows the distribution expected for a constant source.

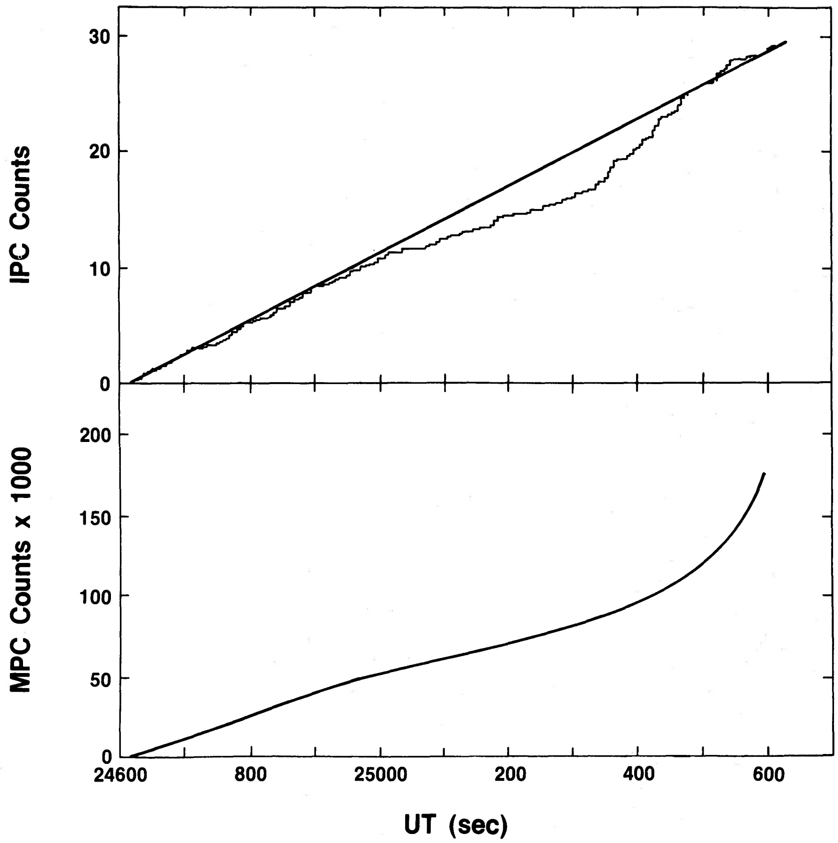

FIG. 7.—(*top*) IPC background counts, 0.5–4 keV, and (*bottom*) MPC coincidence events for the same orbit shown in Fig. 6

variations in better than 1 minute, we adopt $\Delta t = 30$ s as a reasonable estimate of the most rapid time scale of statistically significant variation.

c) Possible Instrumental Origins of the Event

Having established that the statistical significance of the rapid change near 25,400 s is very high,[14] it remains to be investigated whether a systematic effect could be responsible. There is only one scenario we can imagine for a sudden decline in the IPC count rate of hard photons from a steep spectrum source. The IPC is normally subject to sudden drops in voltage between the anode and cathode due to the intrusion of energetic cosmic rays in the gas chamber. These voltage drops, each lasting ~ 1 s, are typically present $\sim 5\%$ of the time (Gorenstein and Fabricant 1979). If the particle intrusion rate were more than 10 times higher than usual, then a sharp decline in the count rate in the upper pulse height channels, as seen in Figure 6, might occur. This might possibly occur in the scan under consideration, because the satellite entered the South Atlantic Anomaly region of high particle density around time 25,460 s. We have made a careful search for an enhanced particle background, or other instrumental effect, that might have caused the event. Our tests include the following:

i) The temporal behavior of detector background, which comprises partly particle events and partly imaged soft X-rays, over a large region of the IPC was examined in several energy bands. Figure 7 (*top*) shows the 0.5–4 keV IPC background. The background rate is rising during the latter part of the scan, as expected due to the proximity of the Anomaly, but at a moderate rate similar to that seen in many other satellite orbits. There is no evidence of the sudden severalfold change in background needed to explain the decline of the hard H0323+022 flux.

ii) The monitor proportional counter contains several detectors that record the particle environment on rapid time scales. None of these MPC background monitors showed an anomaly during the IPC event. One of these background indicators, the "coincidence event" counter, is plotted in Figure 7 (*bottom*). It is an extremely sensitive indicator of the particle environment recorded every 2.56 s and shows no anomaly around 25,400 s. Although the MPC is a good background monitor, it is not sufficiently sensitive to independently confirm the H0323+022 source variation seen in the IPC.

iii) The *Einstein* satellite has a number of other particle background monitors which were examined during the period of interest. These include the IPC "total events," "valid events," "background" counters, and the South Atlantic Anomaly detector. No rapid changes or anomalous behavior was seen in any of these monitors.

[14] Note that the statistical significance of the previously most rapid IPC variation reported from an active galaxy, the quasar 1525+227 = LB 9743 presented by Matilsky, Shrader, and Tananbaum (1982), is considerably lower than that seen in H0323+022. Bin-free comparison of the 107 count arrival times (after removal of data gaps) to a constant flux model gives a significance level of $P = 2\%$ using the Kolmogorov-Smirnov and Smirnov–Cramer–Von Mises tests, compared to 10^{-13} for H0323+022. A χ^2 test using 200 s bins, as discussed by Matilsky *et al.*, gives $P \approx 10^{-4}$ to 10^{-2} depending on where the bin boundaries are set.

iv) The satellite aspect solution was examined, and the IPC image was reconstructed before and during the event. No spatial displacement or distortion in the source is seen, and the aspect solution indicates that the star trackers were in "lock mode." The satellite pointing was thus stable to within several arcseconds during the low flux period. The source photons arrived within 1′ of the detector center, indicating that they did not land on a single cathode wire that may have had an anomalous gain.

Our thorough search for an instrumental cause of the sudden decline in hard IPC flux from H0323+022 uncovered no unusual behavior in the satellite performance, detector status, or particle environment. In particular, the background and soft X-ray source photons measured in the IPC itself indicate that the equipment was performing normally.

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