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B2 1308+326: PHOTOMETRY AND POLARIZATION DURING THE OUTBURST OF 1978 SPRING

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ABSTRACT

The results of visual, infrared, millimeter, and centimeter wavelength photometry and polarimetry of the 1978 spring outburst of the BL Lacertae object B2 1308+326 are reported. The object exhibited a high degree of visual polarization that was rapidly variable in degree and position angle on a time scale of approximately 15 minutes (statistically significant at greater than 99.9% confidence). Following the maximum observed luminosity, the visual radiation declined more rapidly than the infrared. There has been a gradual increase in the flux density at centimeter wavelengths, but the relationship to the optical and infrared activity is unknown. Some implications of the observations are discussed briefly. Other observers are urged to follow the remarkable activity of this object.
Subject heading: BL Lacertae objects

I. INTRODUCTION

In early 1977, the BL Lacertae object B2 1308+326 exhibited an outburst during which changes in the 0.36–3.5 μm spectral flux distribution (F_ν versus ν) were observed (O'Dell *et al.* 1978*b*). The spectral flux at centimeter wavelengths has been increasing slowly since 1977 August, and another outburst at visual-infrared wavelengths has been observed in 1978. It is the purpose of this *Letter* to present photometric and polarimetric results obtained during 1978 April–July at visual and infrared wavelengths (using the 1.5 m telescope at the University of Minnesota/UCSD Mount Lemmon Observing Facility), millimeter wavelengths (using the NRAO 11 m telescope on Kitt Peak) and centimeter wavelengths (using the NRAO three-element interferometer at Green Bank and the 26 m radio telescope at the University of Michigan). To define better the radio spectral characteristics of the source, these data have been supplemented with spectral fluxes between 318 MHz and 90 GHz obtained in 1977 December–1978 February (Owen, Spangler, and Cotton 1978).

The recent outbursts in B2 1308+326 demonstrate that it belongs in the class of highly active objects. The recent determination of its redshift (z = 0.996, Miller 1978) places it at present among the most luminous objects known. It is hoped, therefore, to call attention to the important characteristics of the source so that all interested observers will be encouraged to study it further.

II. PHOTOMETRIC RESULTS

Photometric data on B2 1308+326 covering the period up to 1978 February have been discussed in detail in a previous publication (O'Dell *et al.* 1978b). Subsequent data at visual and infrared wavelengths indicate that another outburst occurred in this object during 1978 spring. Maximum observed fluxes in this outburst were approximately 70% as large as during the peak of the outburst of 1977 spring. The flux levels, $\nu_0 F_{\nu_0}$ and spectral indices, α, of the power-law [$F_\nu = F_{\nu_0} (\nu/\nu_0)^{-\alpha}$] fits to the visual and infrared radiation for data summarized in Table 1 and in O'Dell *et al.* (1978*b*) are plotted versus time in Figure 1. No attempt has been made to correct the data for interstellar extinction as the source is located at a high galactic latitude (b = 83°).

During the 1977 spring outburst, the 0.36–3.5 μm spectral flux distribution was observed to change in shape due to statistically significant decreases in the infrared spectral index during the transitions occurring before and after the maximum observed flux. The resulting behavior was that the infrared radiation increased with time more rapidly than the visual wavelength radiation before maximum light was obtained. The shape of the 0.36–3.5 μm spectral flux distribution was close to that of a power law with $\alpha \approx$ 1.4 at the time of maximum observed flux. Following

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TABLE 1

Magnitudes and Fluxes for Visual and Infrared Data of B2 1308+326

Date (UT)	0.36 μm 845 THz	0.43 μm 702 THz	0.55 μm 548 THz	0.69 μm 435 THz	1.25 μm 240 THz	1.65 μm 182 THz	2.28 μm 131 THz	3.5 μm 86 THz	α	F_{ν_0}
78.04.06....	...	...	...	...	13.36±0.19	...	11.66±0.11	σ=11.3	1.04±0.36	12.3±1.2
					6.8±1.3		12.8±1.4	16.9(2σ)		
78.04.07....	15.04±0.06	15.61±0.06	15.24±0.05	14.53±0.06	...	...	...	...	1.49±0.12	3.16±0.09
	1.62±0.10	2.22±0.13	2.92±0.15	4.53±0.27						
78.04.11......	15.44±0.08	16.03±0.06	15.62±0.06	15.06±0.05	...	...	...	...	1.33±0.12	2.10±0.06
	1.12±0.09	1.51±0.09	2.06±0.12	2.78±0.14						
78.04.16....	15.06±0.06	15.58±0.07	15.28±0.05	14.64±0.09	...	...	...	...	1.33±0.14	2.97±0.12
	1.59±0.10	2.28±0.16	2.82±0.14	4.09±0.37						
78.04.18....	...	...	...	...	...	12.45±0.19	11.26±0.11	...	1.75±0.67	17.3±1.7
						10.4±2.0	18.5±2.0			
78.05.04....	15.15±0.06	15.76±0.06	15.43±0.05	14.74±0.05	...	...	...	...	1.37±0.11	2.66±0.08
	1.46±0.09	1.94±0.12	2.45±0.12	3.73±0.19						
78.05.08....	15.32±0.06	15.94±0.06	15.53±0.07	14.89±0.09	...	...	...	...	1.36±0.16	2.34±0.09
	1.25±0.08	1.64±0.10	2.24±0.16	3.25±0.29						
78.05.09....	15.38±0.07	15.90±0.06	15.52±0.05	14.85±0.05	...	...	...	...	1.52±0.12	2.39±0.07
	1.18±0.08	1.70±0.10	2.26±0.11	3.37±0.17						
78.06.01....	14.89±0.06	15.66±0.06	15.22±0.05	14.50±0.05	...	...	...	...	1.42±0.11	3.25±0.10
	1.85±0.11	2.12±0.13	2.98±0.15	4.66±0.23						
78.06.02....	...	...	...	...	13.00±0.19	12.25±0.10	11.43±0.06	σ=10.8	0.78±0.26	15.3±0.8
					9.5±1.8	12.5±1.3	15.8±0.9	27.(2σ)		
78.07.01....	15.68±0.12	16.18±0.13	15.75±0.13	15.00±0.16	...	...	...	...	1.72±0.28	1.97±0.16
	0.90±0.11	1.31±0.17	1.83±0.24	2.94±0.47						
78.07.03....	...	...	...	...	13.28±0.17	12.63±0.09	11.56±0.06	...	1.22±0.24	13.2±0.7
					7.3±1.2	8.8±0.8	14.0±0.8			
78.07.05....	15.91±0.08	16.50±0.06	15.96±0.07	15.23±0.05	...	...	...	...	1.81±0.12	1.58±0.05
	0.73±0.06	0.98±0.06	1.51±0.10	2.38±0.12						

Note.—Fluxes are listed in mJy, and quoted uncertainties are ± 1 σ. α and F_{ν_0} are the results of least-squares power law ($F_\nu = F_{\nu_0}(\nu/\nu_0)^{-\alpha}$) fits to the data where ν_0 = 540 THz for visual data and ν_0 = 136 THz for infrared data.

the maximum, the infrared fluxes did not decrease with time as rapidly as the visual fluxes.

No infrared observations of the source were made prior to the onset of the 1978 spring outburst due to the source's proximity to the Sun and to a lack of favorable weather. Thus, the behavior of the visual-infrared spectral flux distribution during the period of minimum light between the 1977 spring and 1978 spring events is not known from this work.

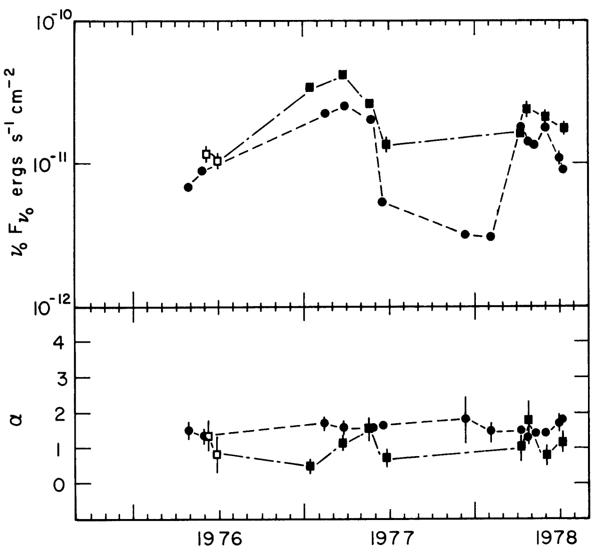

Fig. 1.—Monochromatic energy flux ($\nu_0 F_{\nu_0}$) and spectral index (α) are plotted versus time (in months) for B2 1308+326. The square symbol refers to power-law fits in the infrared (ν_0 = 136 THz) while the circular symbol refers to fits at visual frequencies (ν_0 = 540 THz). One sigma error bars are shown where appropriate. Open symbols are used for measurements made with a 1 mm (9″) aperture, and filled symbols are used for 2 and 3 mm (18″ and 27″) aperture measurements. Lines have been drawn in to enhance the distinction between the infrared and visual sets of data and therefore should not be interpreted as representing the exact nature of possible variations occurring in this source.

At the time of maximum light of the 1978 spring outburst the shape of the 0.36–3.5 μm spectral flux distribution was once again close to that of a power law with spectral index $\alpha \approx 1.4$. During the decline phase of this outburst the flux of visual light decreased more rapidly than the infrared. Although the results displayed in Table 1 and Figure 1 suggest that the variation in this case was due more to a change in the visual spectral index than to a change in the infrared spectral index, this activity is in general agreement with the postmaximum behavior of the 1977 spring outburst in B2 1308+326 and of previously observed outbursts in AO 0235+164 and PKS 0735+178 (O'Dell *et al.* 1977; O'Dell *et al.* 1978*b*). Thus, it appears that the more rapid decline of visual compared with infrared light following maximum is a general characteristic of these events, although no single, simple explanation for all the specific cases involved has been found.

At centimeter wavelengths the total spectral flux increased by about 25% between 1977 August and 1978 August, as shown in Figure 2. The flux appears to have peaked in 1978 July or August. Compared to the variations observed at visual-infrared wavelengths, the changes at centimeter wavelengths occur with a much longer time scale and a much smaller amplitude. This level of activity is not uncommon at centimeter wavelengths (e.g., Altschuler and Wardle 1976). More observations are required to establish the physical relationship, if any, between the activity observed in the two parts of the spectrum.

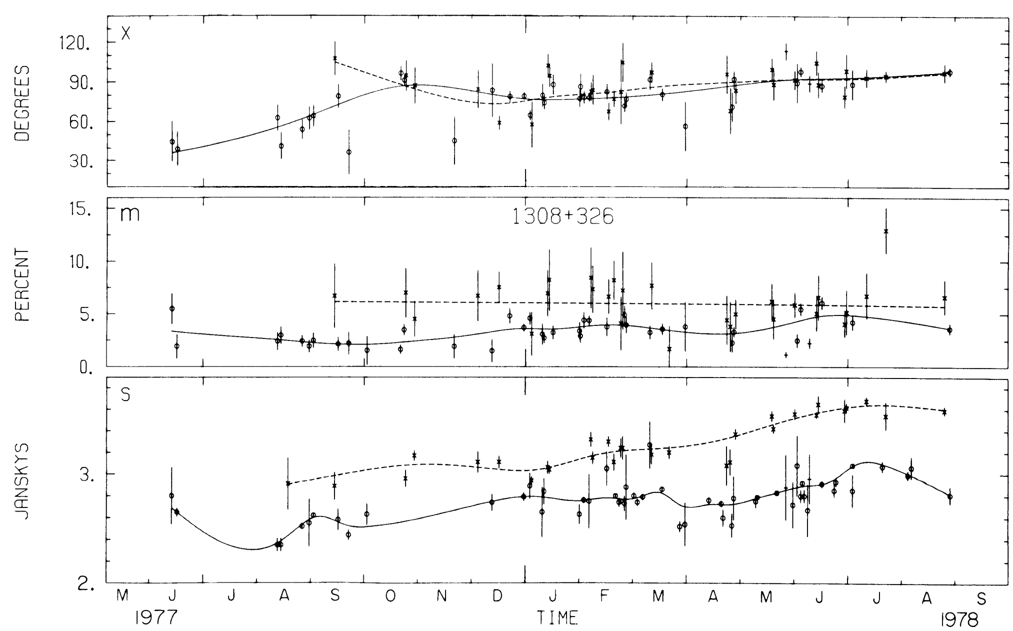

Fig. 2.—The spectral flux, percent linear polarization, and position angle for B2 1308+326 at 6.3 cm (+), 3.8 cm (O), and 2.1 cm (×). Smoothing cubic splines have been fit to the data at 3.8 cm (*solid curve*) and at 2.1 cm (*dashed curve*).

III. POLARIMETRY

Polarization data on B2 1308+326 were obtained at 0.44 μm, 2.28 μm, 9 mm (33 GHz), 3.7 cm (8.1 GHz), and 11.1 cm (2.7 GHz) in 1978 April and May, at 6.3 cm (4.8 GHz) in 1978 May and June, and at 2.1 cm (15 GHz) and 3.8 cm (8 GHz) from 1977 June through 1978 August. Visual and infrared measurements were made throughout the course of the outburst of 1978 spring. The general procedures for obtaining and reducing the data are described elsewhere (Aller 1970; Rudnick *et al.* 1978). Table 2 summarizes the polarization data obtained on B2 1308+326 during 1978 April–July. Figure 3 displays the observed decimeter to millimeter spectral flux distribution and the degree and position angle of polarization as a function of wavelength.

The measurements at 0.44 μm and 2.28 μm consisted of a series of two or more integrations (each 10–30 minutes in duration) using the same telescope alignment. As a statistical test for variations with time, the value of χ^2 has been calculated for each of the measured Stokes parameters (I, Q, U) under the assumptions that the deviations are Gaussian with the uncertainties determined from the least squares analysis of the data and that the parameter's value is constant with time. For the three cases where statistically significant variations (confidence levels greater than 99.9%) in one or more Stokes parameters have been noted, each result of the series of integrations has been listed in Table 2. In the cases where the χ^2 analyses indicate that no statistically significant variations have occurred, the individual integrations have been combined to yield a single nightly value.

The most spectacular characteristic of the polarization of this source is the high degree of variability observed at 0.44 μm. Not only is there strong evidence for variability on time scales of days and months, there is also evidence (confidence levels greater than 99.9%) that on three separate occasions—1978 May 8, July 1, and July 5—significant variations in the degree of polarization and/or the position angle occurred during a period of about 15 minutes! Polarimetry with comparable time resolution at 0.44 μm of the BL Lacertae objects PKS 0735+178, OJ 287, B2 1101+384, and B2 1652+398 shows no evidence at all for similar behavior in these sources which were relatively inactive during the period of observations (Puschell and Stein 1979). J. R. Angel (private communication) and his collaborators at the Steward Observatory measured the visual polarization of B2 1308+326 on several occasions between 1978 May 10 and 1978 June 2. Although their results show that the visual polarization varied significantly during this period, time scales as short as those reported here were not noted. As shown by the results displayed in Table 2, the changes in polarization were not accompanied by any substantial variations in the observed flux.

In contrast to the behavior at visual wavelengths, the percent polarization at centimeter wavelengths appears to have varied slowly. As shown in Figure 2, the linear polarization position angle appears to have changed by about 20° since the beginning of 1978 at

TABLE 2

POLARIMETRY DATA

Date	UT	λ_o(μm)	I(mJy)	Q(mJy)	U(mJy)	m(%)	χ(°)
78.04.06.......	09^h07^m	2.28	13±1	−2.7±1.3	0.4±0.9	19±8	86±15
78.04.07.......	07 19	0.44	2.36±0.07	−0.17±0.04	0.28±0.01	14±1	61±3
78.04.11.......	08 53	0.44	1.52±0.05	0.01±0.03	−0.11±0.02	7±1	139±7
78.04.16.......	08 00	0.44	2.3±0.2	0.02±0.01	0.14±0.03	6±1	40±5
78.04.24.......	...	11.1×10^4	1680±65	27±4	23±4	2.1±0.2	20±4
78.04.24.......	...	3.7×10^4	2820±140	−55±8	12±8	2.0±0.3	84±4
78.05.01.......	...	9×10^3	3300±300	−200±40	1±76	5.8±1.5	90±14
78.05.04.......	06 21	0.44	1.92±0.04	0.01±0.03	−0.02±0.01	0±1	...
78.05.08.......	06 06	0.44	1.65±0.06	−0.04±0.02	−0.25±0.05	15±3	131±3
78.05.08.......	06 14	0.44	1.65±0.05	0.00±0.02	−0.25±0.06	15±4	135±3
78.05.08.......	06 22	0.44	1.67±0.06	0.11±0.09	−0.10±0.01	8±4	158±18
78.05.08.......	06 30	0.44	1.61±0.05	0.04±0.04	−0.01±0.03	2±2	...
78.05.08.......	06 38	0.44	1.66±0.05	0.05±0.04	−0.12±0.02	8±2	147±6
78.05.08.......	06 46	0.44	1.58±0.06	0.02±0.07	−0.07±0.06	0±5	...
78.05.08.......	06 54	0.44	1.67±0.06	0.14±0.06	−0.17±0.01	13±2	155±6
78.05.09.......	07 26	0.44	1.70±0.09	0.08±0.03	−0.22±0.02	14±1	145±3
78.06.01.......	05 47	0.44	2.14±0.08	−0.23±0.03	0.11±0.01	12±1	77±3
78.06.03.......	04 17	2.28	15.7±0.9	−2.5±0.4	−0.9±0.8	16±5	100±9
78.06.06.......	04 49	0.44	2.0±0.1	−0.05±0.01	−0.07±0.05	4±2	119±12
78.07.01.......	05 07	0.44	1.26±0.10	−0.03±0.09	0.06±0.03	3±4	...
78.07.01.......	05 37	0.44	1.32±0.10	−0.11±0.07	0.24±0.03	20±4	57±6
78.07.05.......	04 47	0.44	0.96±0.05	−0.25±0.09	0.13±0.04	28±5	76±7
78.07.05.......	04 57	0.44	1.04±0.06	−0.08±0.08	0.17±0.03	17±5	58±10
78.07.05.......	05 07	0.44	0.99±0.05	−0.01±0.06	0.10±0.05	9±5	48±22
78.07.05.......	05 27	0.44	0.90±0.04	0.08±0.01	0.10±0.06	13±5	26±9

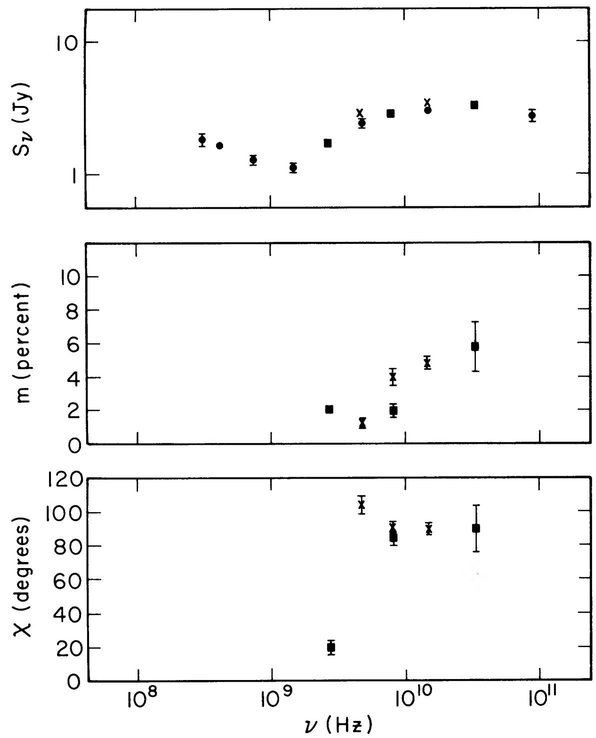

FIG. 3.—The spectral flux, percent linear polarization, and position angle plotted versus frequency in the radio region for B2 1308+326. The data indicated by the square symbol were obtained in 1978 April-May at the NRAO. The circular symbol refers to data taken from Owen *et al.* obtained in 1977 December–1978 February. The data indicated by × are 1978 April–July averages of measurements obtained at the University of Michigan Radio Observatory. The measurements at 318 MHz and 430 MHz were obtained with the Arecibo 300 m telescope; that at 750 MHz with the Green Bank 91 m telescope; those at 1.4 GHz, 5 GHz, and 15 GHz with the VLA; and that at 90 GHz with the NRAO 11 m telescope on Kitt Peak.

both 2.1 cm and 3.8 cm. The degree of polarization has increased significantly at 3.8 cm, but appears to be constant at 2.1 cm.

IV. DISCUSSION

Since the visual polarization variations do not seem to be accompanied by significant changes in flux level, it is difficult to interpret the variations in terms of scattering or absorption by intervening clouds. Similarly, Faraday rotation by intervening matter seems highly unlikely. Therefore, in the absence of ultra relativistic motions, the time scales of the observed polarization variations would suggest that the emitting region (or at least a volume responsible for a sizable fraction ($\gtrsim 30\%$ of the emission) had a radius of $\lesssim 3 \times 10^{13}$ cm. The recently determined emission-line redshift of $z = 0.996$ (Miller 1978) implies for an isotropic radiator that, at the observed maximum flux, the luminosity (obtained by integrating over the observed 0.36–3.5 μm spectral fluxes) is $\sim 10^{48}$ ergs s^{-1}, making these outbursts in B2 1308+326 among the most luminous known.

The maximum mass which can be placed inside a radius of 3×10^{13} cm (i.e., by equating it to the Schwarzschild radius) is $\sim 10^8$ $M_\odot$. It is interesting to note, then, that the Eddington luminosity for this mass is roughly two orders of magnitude smaller than the observed outburst in B2 1308+326, and comparable to the minimum observed luminosity inferred from photographic records communicated by Gottlieb and Liller (1976). If one were to associate the luminosity of such objects with an accretion phenomenon, as is currently popular, this fact would indicate that the emission was nonisotropic (cf., e.g., Icke 1977) and/or that the energy release in the source was impulsive.

If the visual-infrared radiation were produced in the conventional way, isotropically by the synchrotron process, it is of further interest to note that unless the Compton luminosity of the source were even larger than the synchrotron luminosity, the source magnetic field would exceed $\sim 10^6$ gauss (in the rapidly variable volume). The maximum electron lifetimes would accordingly be only a small fraction of a second. One can show within the context of the conventional source model that in most compact extragalactic visual-infrared sources, the electron lifetimes must be shorter than the light travel time across the source (Jones 1979). B2 1308+326 then provides an especially extreme case. One would infer, then, in many sources, that electrons must be more or less continuously accelerated or that the observed emission is not isotropic (possibly due to relativistic streaming, for example).

A high degree of variability makes obtaining truly simultaneous polarization and flux data at various wavelengths very difficult. Therefore, it is difficult to demonstrate that the spectral flux distribution and polarization properties of this object are continuous over the visual to radio frequency range. Electromagnetic propagation effects may further confuse the issue at the lower radio frequencies.

The important spectral and polarization properties exhibited by B2 1308+326 in the radio region (cf. Fig. 3) can be summarized as follows: (1) The spectrum is rather flat at short wavelengths, with a broad peak near 3 cm; (2) the spectrum rises again at decimeter wavelengths; (3) there is a substantial drop toward longer wavelengths in the degree of linear polarization near 3 cm; (4) the polarization position angle is approximately the same at all but the longest wavelength for which it was measured. Property (4) implies the near absence of Faraday rotation at centimeter wavelengths within the source. Properties (1) and (3) suggest that at least part of the source structure is becoming opaque longward of $\sim$2–3 cm, whereas property (2) suggests that there is also some more extended, transparent structure. This may also be indicated by the difference between the two 6 cm (4.8 GHz) spectral flux measurements shown in Figure 3. The flux measured with a single dish exceeds that obtained with the VLA (which would resolve larger scale structure) by about 0.3 Jy, roughly the contribution found by extrapolating the decimeter spectra to 6 cm. The difference between the two flux measurements at 2 cm (15 GHz) shown in Figure 3 may represent a change in flux at that wavelength in the time interval between the two measurements, or slight differences in calibration procedures.

These observations accent the developing picture of active phenomena in QSOs. Although detailed explanations of the various phenomena are beyond the scope of this paper, it is interesting to list some of the facts requiring eventual physical explanation which have been revealed in this and other recent studies:

1. A spectral-flux distribution for which strong millimeter emission apparently correlates with a strong featureless and highly polarized visual-infrared continuum (e.g., Owen and Mufson 1977; O'Dell *et al.* 1978*a;* Rudnick *et al.* 1978).
2. Variability of flux over a wide range of wavelengths with the visual-infrared variability usually stronger than the radio variability (e.g., the present work; O'Dell *et al.* 1978*b;* Carswell *et al.* 1974; Rieke 1972; Kinman *et al.* 1974; Rieke *et al.* 1976; Altschuler and Wardle 1976).
3. Highly variable degree of visual polarization and position angle (e.g., the present work; Carswell *et al.* 1974).
4. Small degree of rotation of visual to infrared position angle of polarization (Rieke *et al.* 1977).
5. Lack in most sources of direct correlation of flux variability and polarization of visual and infrared data with that at the lower radio frequencies (Pomphrey *et al.* 1976; Rudnick *et al.* 1978).

The accumulating evidence continues to support an interpretation in terms of high-energy electron synchrotron radiation over the vast range of wavelengths from the radio regime to the visual. In some cases Compton scattered X-rays may be observed (Margon, Jones, and Wardle 1978).

V. SUMMARY

The outburst of B2 1308+326 that occurred in 1978 spring exhibited the following characteristics:

1. Significant change of shape of the visual-infrared spectral-flux distribution after maximum light. Following the maximum, at which the 0.36–3.5 μm spectral flux distribution was close to that of a power-law with $\alpha \sim 1.4$, the visual wavelength radiation was found to decrease more rapidly than the infrared emission.
2. High polarization at visual, infrared, and millimeter wavelengths.
3. Highly variable visual polarization observed to change on a time scale of approximately 15 minutes.
4. An increase of the spectral flux at centimeter wavelengths with a much longer time scale and smaller amplitude. Concurrently, the degree of linear polarization increased significantly at 3.8 cm.

Many of these properties are typical of outbursts in the highly active QSOs. Detailed interpretation of these properties in terms of physical models should lead us to further conclusions regarding the source of energy generation. Other observers are urged to follow possible further spectacular activity of B2 1308+326.

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