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Radio spectrum of the major outburst in the BL Lacertae object AO 0235+164

This paper presents an analysis of the evolution of the radio emission of AO 0235+164 during the recent large outburst which coincided with the optical and infrared event reported by Kinman and Rieke[1]. The event seems to be the clearest case to date of a correlated radio and optical outburst. Spinrad and Smith[2] suggested that AO 0235+164 is a red BL Lacertae object and noted that it is a radio and optical variable. Two smaller radio outbursts have been observed since 1972.8 by MacLeod *et al.*[13] and, based on their data and that of J. C. Webber (private communication), the quiescent flux density level of the source at frequencies > 1 GHz is < 1 Jy (1×10^{-26} W m^{-2} Hz^{-1}). The recent event described here offers an unusual opportunity to study an isolated outburst because its amplitude was much larger than the quiescent flux level, good coverage in time at two radio frequencies was obtained, and simultaneous observations over a wide range of radio, infrared, and optical frequencies were made.

The radio flux density data are presented in Tables 1 and 2. The measurement at 2.7 GHz was made with the 300-foot antenna of the National Radio Astronomy Observatory. Observations of flux density and linear polarisation at 4.9, 8.0 and 14.5 GHz were made with the University of Michigan 85-foot paraboloid using a previously described technique[3]. The measurements at 31.4 and 85.2 GHz were made with the 36-foot antenna of the NRAO as part of a millimetre wave variable-source programme being conducted by Hobbs and Dent. Included in Table 2 are a flux density measurement at 5 GHz made with the NRAO 300-foot antenna by J. W. Warner and J. H. Black (private communication) and the average of observations on two days at 90 GHz by B. J. Wills[4].

The characteristics of the observed radiation are consistent with the synchrotron radiation process. The emission extended over a broad range of frequencies; and the source was linearly polarised during the outburst by up to 3% at both 8 and

Fig. 1 The flux density against UT date at 14.5 (×) and 8.0 (○) GHz. The arrows labelled *a*, *b*, *c*, *d* indicate the epochs of the spectra shown in Fig. 2.

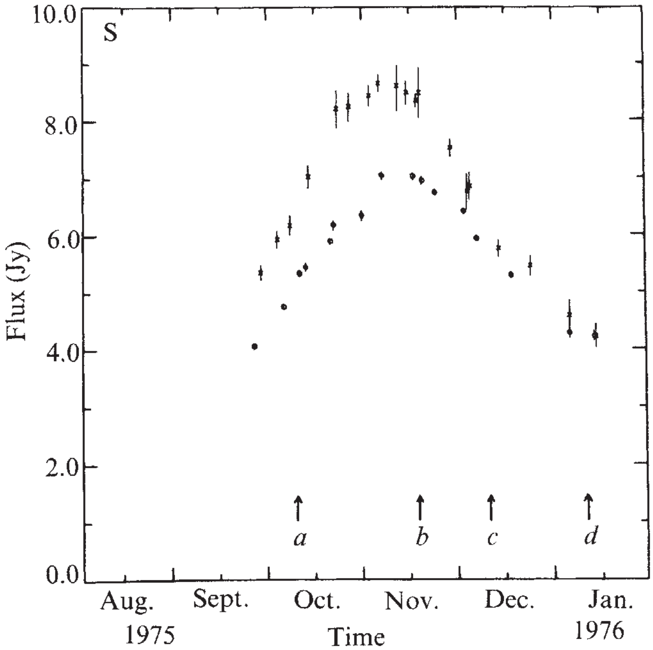

Table 1 Flux density variations with time*

Date (UT)	8.0 GHz S_ν (Jy)	8.0 GHz σ_s (Jy)	14.5 GHz S_ν (Jy)	14.5 GHz σ_s (Jy)
August 1974				
19	1.21	0.09		
September 1975				
27	4.05	0.06		
29			5.34	0.13
October 1975				
4			5.93	0.16
6	4.74	0.05		
8			6.17	0.18
11	5.33	0.07		
13	5.44	0.08		
14			7.02	0.20
15			7.21	0.59
21	5.89	0.06		
22	6.18	0.09		
23			8.20	0.34
27			8.24	0.26
31	6.34	0.10		
November 1975				
3			8.43	0.19
6			8.64	0.16
7	7.04	0.08		
November 1975				
12			8.60	0.45
15			8.48	0.21
17	7.02	0.08		
18			8.35	0.13
19			8.48	0.45
20	6.95	0.08		
24	6.74	0.07		
29			7.52	0.16
December 1975				
3	6.41	0.06		
4			6.75	0.32
5			6.84	0.25
7	5.93	0.05		
14			5.75	0.15
18	5.28	0.06		
19			6.31	0.50
24			5.45	0.18
January 1976				
6	4.26	0.09	4.57	0.27
13	4.23	0.10	4.21	0.21

* Observations made with University of Michigan 85-foot antenna.

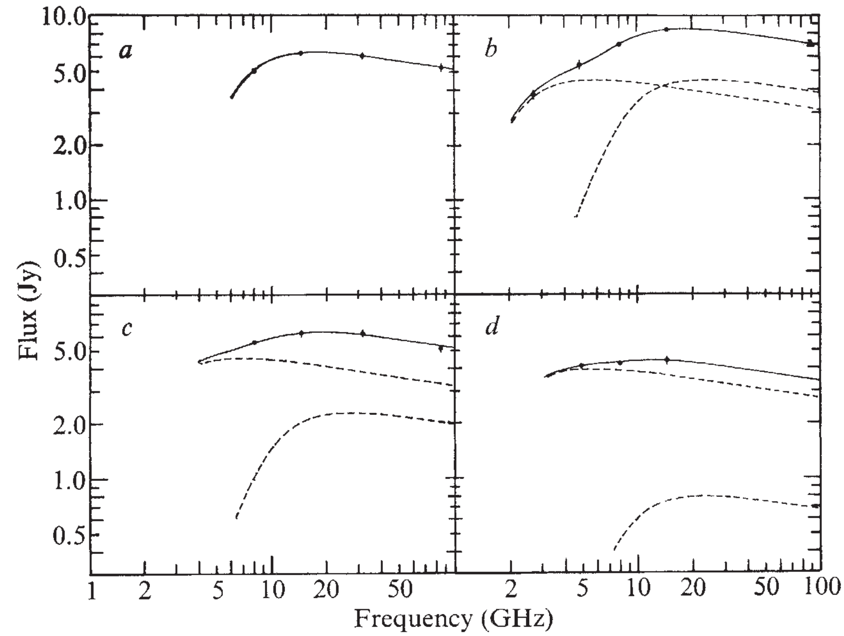

Fig. 2 Spectrum of AO 0235+164 at four epochs: *a*, October 9, 1975; *b*, November 18, 1975; *c*, December 10, 1975; and *d*, January 10, 1976. The solid curves were fitted to the data by summing the two self-absorbed homogeneous synchrotron source spectra shown as dashed lines. The values shown at 8.0 and 14.5 GHz are interpolations of the data shown in Fig. 1. In *b* the 5-GHz data point is an average of two measurements made on November 4 and November 24, 1975 and the 90-GHz data point is an average of measurements made on November 20 and November 21, 1975.

14.5 GHz and to a higher degree at optical frequencies[4]. A preliminary analysis of our linear-polarisation data indicates no significant difference between the observed polarisation position angles at 8 and 14.5 GHz, which is consistent with the hypothesis that there is no Faraday rotation within the source. The polarisation position angle at 14.5 GHz during early October 1975 was $162\pm8°$ which agrees, within our error, with the polarisation position angle observed at optical wavelengths by Kinman[4] on October 3, 1975. This agreement certainly suggests that the radio and optical radiation originated in regions having the same magnetic-field orientations, but the much lower degree of polarisation at 14.5 GHz ($2.2\pm0.6\%$) indicates that the magnetic field in the radio-emitting region is less well ordered. These polarisation data are evidence of a direct association between the optical and radio-emitting regions.

The time dependence of the radio outburst at 8.0 and 14.5 GHz is shown in Fig. 1. Before the maximum in mid November the fractional rate of increase was the same ($1.7\%\ d^{-1}$) at the two frequencies. The maximum at 14.5 GHz seemed to occur on November 8 which was ~ 6 d before the apparent maximum at 8.0 GHz. Such a delay is qualitatively consistent with expanding synchrotron-source models, but the observed ratio of 1.2 for the flux densities at maxima is significantly less than the ratio of 2.0 predicted by the instantaneous injection model[5]. The observed behaviour of the flux density at the two frequencies could be explained by either a prolonged injection or an acceleration of radiating particles from August through mid November 1975 (ref. 6). The complex light curve at infrared and optical wavelengths also reached a maximum in mid November[4] and appears to be direct evidence of just such a prolonged injection.

Table 2 Spectral data

Date (UT)	Frequency (GHz)	S_ν (Jy)	σ_s (Jy)	Antenna
October 9, 1975	31.4	6.09	0.21	36′ NRAO
	85	5.21	0.27	36′ NRAO
November 5, 1975	4.9	5.47	0.32	85′ Univ. Michigan
November 18, 1975	2.7	3.74	0.20	300′ NRAO
November 20.5, 1975	90	6.97	0.20	36′ NRAO
November 24, 1975	5.0	5.70	0.30	300′ NRAO
December 10, 1975	31.4	6.24	0.18	36′ NRAO
	85	5.04	0.10	36′ NRAO
January 10, 1975	4.9	4.10	0.15	85′ Univ. Michigan

The observed radio spectra of the source at four epochs are displayed in Fig. 2. The most striking feature of three of the spectra is the broad low frequency turnover which cannot be fitted by a single homogeneous, self-absorbed synchrotron emitting region but which is characteristic of inhomogeneous synchrotron sources[7]. As the simplest representation of the spectrum of an inhomogeneous source, we have summed the spectra (shown as dashed lines) of two homogeneous emitting regions which become self-absorbed at different frequencies. The progressive flattening of the spectrum at <14.5 GHz after the maximum in mid November (see Fig. 1) is consistent with the turnover progressing towards lower frequencies. This phenomenon is illustrated by the systematic decrease in the amplitude of the high frequency spectral component in Figs 2*c* and 2*d*. Above 30 GHz the source was completely transparent during the period of observation, and our data are consistent with the spectral index α remaining constant at $\alpha = -0.15$. The fact that the source was transparent before reaching maximum is inconsistent with instantaneous-injection expanding source models. It requires that the injection or acceleration of the radiating particles was prolonged and that energy was supplied to the radiating particles more rapidly than it was lost due to expansion of the emitting region. Synchrotron and inverse Compton energy losses seem to have been unimportant for particles radiating at < 100 GHz, as there was no significant steepening of the spectrum with time.

An extrapolation of the radio spectrum in mid November predicts a $\lambda = 20$ μm flux density of 3 Jy compared with an observed flux of 1 Jy (ref. 4). The continuity between the radio and infrared fluxes suggests that the emission over the entire spectrum is produced by synchrotron radiation. The observed spectral index of -1.2 in the infrared and -3.8 at optical wavelengths[2,4] indicates that the synchrotron emission cuts off in the latter spectral region.

A quantitative analysis of the observed emission places additional constraints on models for the source because of the apparent high brightness temperature implied by the rapidity of the variations. Based on the observed fractional rate of change of the flux density, the apparent radius of the source must be $\lesssim 100$ light d. Two absorption line redshift systems, with $z = 0.524$ and $z = 0.851$, have been observed in the optical spectrum[4]. The larger redshift would correspond to a cosmological distance of $\sim 6\times10^9$ pc. This distance and apparent physical size yields an angular diameter of 2×10^{-5} arc s and implies an apparent source brightness temperature of $T_b \simeq 10^{15}$ K at 8 GHz. Such a high intensity would result in the inverse Compton process[8,9] producing a much larger flux of infrared and shorter wavelength radiation than was observed. The observed maximum flux density in the optical B band of 3.7×10^{-3} Jy (ref. 4) can be used to set an upper limit on the radio brightness temperature[10] of $\sim10^{12}$ K at 8.0 GHz. The disparity between this upper limit and the apparent observed brightness temperature is eliminated if the source expands with a relativistic velocity[10,11] or if it is much closer than the cosmological distances associated with the observed redshifts. An expansion velocity corresponding to a Lorentz factor of ~ 10 is sufficient to reduce the brightness temperature in the reference frame of the emitting region to $< 10^{12}$ K and would make the inverse Compton process energetically unimportant in the source. A relativistic expansion of the source would also produce a broadening in the low-frequency self absorption turnover of the spectrum[12] which is qualitatively consistent with our observed radio spectra of AO 0235+164.

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Photometric and spectroscopic observations of the BL Lacertae object AO 0235+164

BL LACERTAE objects pose, in extreme form, the question of the nature of the most energetic extragalactic sources. They exhibit rapid variability over a large dynamic range, large and variable intrinsic polarisation, and high luminosity, a combination that is very difficult to reconcile with current physical theory. In this paper, we confirm that AO 0235+164 is a BL Lacertae object with one absorption-line redshift at $z = 0.524$ and a probable one at $z = 0.852$. Photometry between 0.36 and 21 μm and at 90 and 140 GHz showed a peak luminosity in November 1975 comparable with the most luminous QSOs.

Extensive studies in the optical and radio spectral regions have documented the variations in flux and polarisation for a number of these sources[1,2]. The available infrared observations are far less complete, even though BL Lac-type objects emit a large, frequently dominant, portion of their energy in this spectral region. Coordinated programmes to study the behaviour of these sources in all three spectral regions are needed.

Their lack of emission lines has made it difficult even to estimate the distances of these sources. Two absorption lines identified as the Mg II doublet redshifted by $z = 0.424$ have, however, been found in the spectrum of one of these objects (PKS0735+178) (ref. 3). In addition, BL Lac itself and some probably similar objects (1101+38, 1652+39; ref. 2) have surrounding nebulosity which shows absorption lines at redshifts of $z < 0.1$.

AO 0235+164 is a newly discovered member of this class of object. Based on the coincidence of precise optical and radio positions, it was identified by Argue, Kenworthy, and Stewart[4] with a 19-mag, apparently stellar object. Spinrad and Smith[5] found that the optical object had a featureless spectrum at wavelengths > 4,400 Å and varied between $V = 17.5$ and 19.5 during 1972–74. They reported that the object was red ($B–V \simeq 1.3$) and had an apparent faint wisp of nebulosity extending 3″ S from the stellar source. Spinrad and Smith also cited radio observations that show a spectrum rising with increasing frequency and indicate variability at 6 cm; they suggested that AO 0235+164 is a BL Lac-type object with an unusually red colour.

The outburst of AO 0235+164

We have studied the recent outburst of this source in which it reached a magnitude of $V = 14.3$. Its spectrum has a strong and rich absorption-line system at $z = 0.524$, and probably a second system at $z = 0.852$. If these redshifts are of cosmological origin, AO 0235+164 reached a peak luminosity $\geqslant 3\times10^{14}L_{\odot}$, comparable with the outputs of the most luminous QSOs. Most of this energy fell in the infrared. AO 0235+164 is one of the most rapid variables and has one of the largest amplitudes and linear polarisation in the optical region found for any QSO-like object. Extensive observations show that the shape of the infrared spectrum fluctuated during the outburst. Our radio observations supplement those reported in papers by MacLeod *et al.*[27] and Ledden *et al.*[6] which provide a thorough record of the outburst in this spectral region.

On October 3, 1975, UT, AO 0235+164 was 2 mag brighter than its brightest reported by Spinrad and Smith. On the following night, it had brightened by a further 0.18 mag. Further photoelectric photometry, obtained occasionally during the outburst, was supplemented by photographic observations of the *B* magnitude. All of these measurements are summarised in Table 1 where they have been converted to flux densities using the calibration of Johnson[7]. The linear polarisation of AO 0235+164, measured with an unfiltered S-11 photocathode at the Kitt Peak National Observatory (KPNO) 4-m telescope, was 24.6±0.5% at a position angle of 154.2° on October 4, 1975, UT, and only 6.1±1.2% at a position angle of 126.4° on January 4, 1976, UT.

Measurements

The large range and rapidity of the optical variations and the high and varying polarisation are characteristic of BL Lac-type objects and confirm the classification by Spinrad and Smith. It is noteworthy that the *B–V* colour (0.98 mag) was about the same as that found by Spinrad and Smith before the source had brightened by more than a factor of 10. The *UBV* colours of AO 0235+164 are similar to those of weak-lined red degenerate stars and are slightly redder than those of weak-lined subdwarfs, emphasising the importance of precise optical and radio positions for identifying objects of this type.

Infrared measurements, also summarised in Table 1, were begun on October 7, 1975, UT. It was possible to observe the source approximately every two weeks during the outburst because of a fortuitous arrangement of telescope schedules. Near maximum, AO 0235+164 was sufficiently bright that complete infrared spectra extending from 1–21 μm could be obtained. The star α Ari was used as a flux standard and the photometry was reduced according to the calibration described by F. J. Low[28]. Where appropriate, the measurements