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The discovery of a microarcsecond quasar: J 1819+3845

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ABSTRACT

We report on the discovery of a source which exhibits over 300% amplitude changes in radio flux density on the period of hours. This source, J 1819+3845, is the most extremely variable extragalactic source known in the radio sky. We believe these properties are due to interstellar scintillation, and show that the source must emit at least 55% of its flux density within a radius of <16 microarcseconds at 5 GHz. The apparent brightness temperature is $>5.10^{12}$ K, and the source may be explained by a relativistically moving source with a Doppler factor ~ 15. The scattering occurs predominantly in material only a few tens of parsecs from the earth, which explains its unusually rapid variability. If the source PKS 0405-385 (Kedziora-Chudczer et al 1997) is similarly affected by local scattering material, Doppler factors of ~ 1000 are not required to explain this source. The discovery of a second source whose properties are well modeled by interstellar scintillation strengthens the argument for this as the cause for much of the variations seen in intra-day variables (IDV).

Subject headings: ISM: general – quasars: individual(J 1819+3845) – radiation mechanisms: nonthermal

1. Introduction

Variability in extragalactic radio sources is used to probe the smallest regions of these sources. Many flat-spectrum quasars and BLLacs are intrinsically variable (Aller et al, 1985), typically on timescales of weeks to years. A class of rapid variables – the intraday variables (IDV, Witzel et al, 1986) – have recently attracted attention. If the observed variations in these sources are intrinsic, then causality implies brightness temperatures far in excess of the Compton Catastrophe limit (when all the energy in synchrotron radiating electrons should be rapidly converted to X-ray photon energy.) To resolve this problem it has been suggested that the variations are not intrinsic, but due to a propagation effect known as scintillation, but the question remains unresolved (see Wagner & Witzel, 1995).

Interstellar scintillation is demonstrated in pulsars at radio frequencies (Rickett, 1977), and is probably responsible for low frequency variability in flat spectrum radio sources (Rickett et al, 1984). The discovery of dramatic variability at GHz frequencies in PKS 0405-385 was explained by Kedziora-Chudczer et al. (1997) as a scintillation effect.

In this *Letter* we report on the discovery of a source whose variations are also best explained as a scintillation effect. J 1819+3845 is a faint ~ 21 mag quasar at 18h19d26.55s +38d45m01.8s (J2000). An optical spectrum obtained at the INT on 1999 May 10, showed broad emission lines at z=0.54. The radio source has no detected extended emission, and has a rising radio spectrum (fig.1) with $\alpha \sim -0.5$ (we use $S \propto \nu^{-\alpha}$).

Throughout the paper we assume a q_o=0.5, Λ=0 cosmology with $H_o = 65\,\mathrm{kms^{-1}Mpc^{-1}}$.

2. Observations

Observations of J 1819+3845, as a member of a sample of about 50 CLASS (Myers et al., 1999) sources, started in January 1999 with two flux den-

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sity measurements separated by 4 days. These indicated a factor 2 variation in flux density. A further 10 observations, at a variety of time intervals, were made in late March 1999. These showed the same flux density range and indicated that the variability timescale was at most an hour. A long 96 hour campaign was then conducted from May 13 UT 0300 until May 17 0300 to study J 1819+3845, as well as other sources. Here we report only on the observations of J 1819+3845.

The observations were obtained with the new WSRT Multi Frequency Frontends (MFFEs) (see http://www.nfra.nl/wsrt). Data were taken at 1.4, 2.3, 4.9 and 8.4 GHz using a backend with 8 contiguous bands, each of 10 MHz bandwidth. Standard calibrators were observed for about 5 min once every hour for amplitude and phase calibration. The Baars et al. (1977) flux scale was used for 3C286 and all other sources are tied to 3C286.

In the 96 hour campaign we observed J 1819+3845 for two 12 hour periods with two sub-arrays each of 6 telescopes which had frontends tuned to a different frequency and a total bandwidth of 4×10 MHz. On May 13/14 we observed at 4.9/1.4 GHz, the following night we observed at 4.9/8.4 GHz. The time resolution was 30 seconds for the split-array observations, and 10 seconds for all other data. With a source flux density of typically 100 mJy, noise was clearly insignificant (see table 1).

The normalized rms fluctuations $S_{rms}/<S>$ (modulation index, m) are calculated for each 12 hour run, and for the intermittent observations over the full 96 hours, and tabulated in table 1. The error is obtained by calculating m in the first and last half of the run independently. The characteristic timescale of the fluctuations is calculated by use of the structure function D^1 (see e.g. Simonetti, Heeschen & Cordes, 1985). The characteristic timescale is taken as twice the time for D^1 to reach $(1-e^{-1})\mathrm{D}^1_{max}= (1-e^{-1})2m^2$. This corresponds to the full-width at $1/e$ of the autocorrelation function. The structure function has been corrected for noise bias using $2\sigma^2_{\delta f}$, in the manner of Simonetti et al (1985).

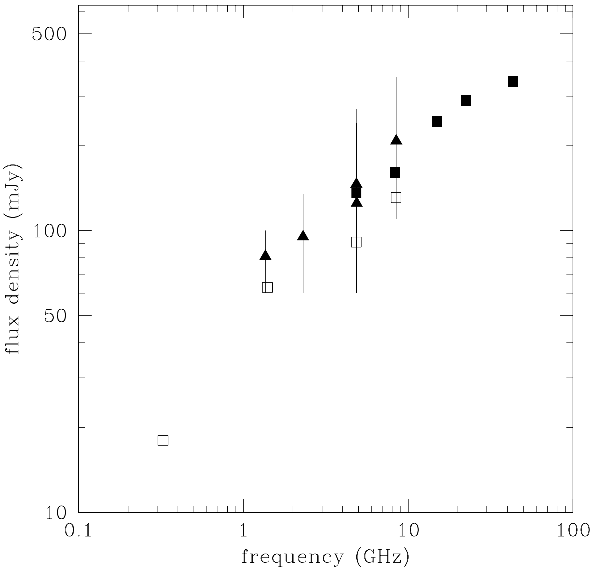
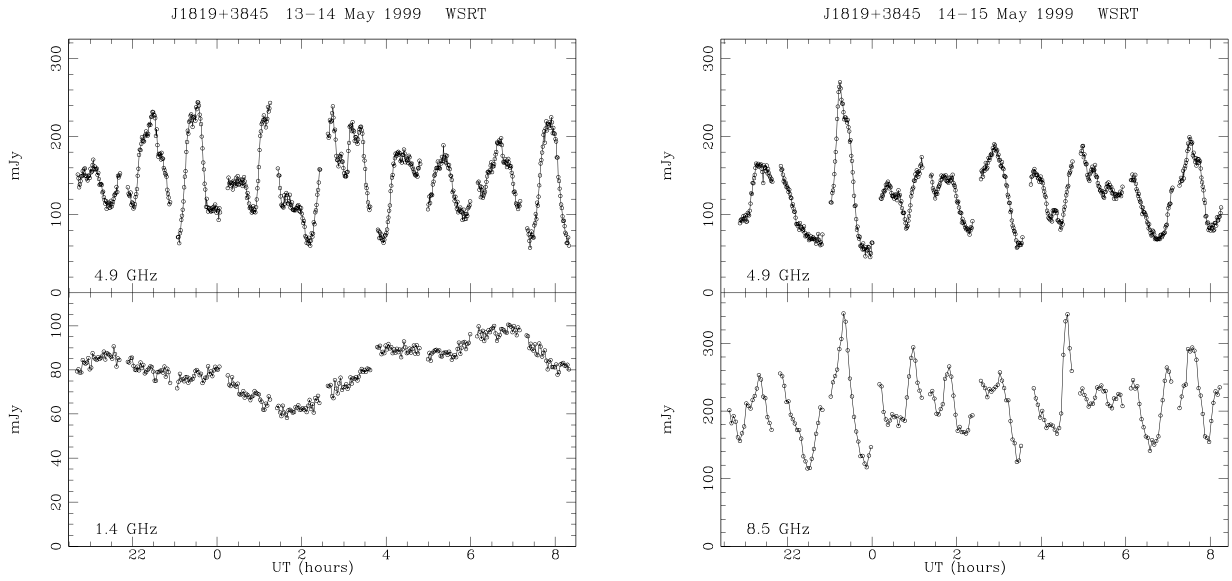


Fig. 1.— Radio spectrum of J 1819+3845. The open symbols are survey data (WENSS, NVSS, GB6, CLASS). The filled symbols are new observations: squares VLA (Mar 98); triangles mean WSRT flux densities. Error bars for all observations fall within the symbols. The vertical lines indicate the flux density range in the WSRT oberservations reported here.



(a) (b)

Fig. 2.— The light curves of J 1819+3845 at (a) 12 hour WSRT split-array observations at 1.4 and 4.9 GHz. (b) 4.9 and 8.5 GHz.

3. Source size and structure

If the variations are intrinsic then the source size must be of the order of a light-hour. At a redshift 0.54, this corresponds to nanoarcseconds. A source this small will necessarily scintillate, so we only consider this as the cause of the short timescale variations.

Weak scintillation occurs at high frequencies where the diffractive scale of the turbulence is smaller than the Fresnel scale. At lower frequencies two different branches of scintillation develop: refractive and diffractive (see Narayan 1992 for a clear exposition). The transition between the regimes of diffractive/refractive scintillation and weak scintillation occurs at a critical frequency, when the refractive, diffractive and Fresnel scales are equal. In order to show large modulations at this frequency, the apparent source size must be smaller than, or comparable to, the Fresnel scale i.e. $\sqrt{\lambda/2\pi L}$, where L is the distance to the ‘equivalent screen’. At the critical frequency there is a very characteristic peak of the modulation index of broad-band scintillations. The intensity of the fluctuations in J 1819+3845 peaks around 5 GHz and the timescales of the modulations get much longer below this frequency, similarly to PKS 0405-385 (Kedziora-Chudczer et al 1997), providing strong evidence for scintillation as the cause of the variations (table 1, fig.3).

The timescale at the critical frequency is $\approx \sqrt{\lambda L}/v$. The timescales of the variations in J 1819+3845 at (the close to critical) frequency 5 GHz occur much too rapidly for the equivalent screen to be at a distance of ∼1 kpc, as in the model of Walker (1998). For a relative screen–earth velocity of 50 km/s (typical earth rotation speed around the sun) this predicts a FWHM timescale of ∼ 6 hr.

Using the measured timescale of the variations and the critical frequency, we can solve for the scattering measure (or equivalently $C_N^2=10^4\,C_{-4}$; Armstrong et al, 1981), the radius of the scattering disk (Θ), and the distance to the equivalent screen (L), if we assume the relative transverse velocity of source–screen projected onto the earth (v). The scattering disk Θ corresponds to maximum source radius for full scintillation. The apparent source velocity projected onto a screen within our Galaxy is less than a few km/s, even for apparent source speeds of $10c$, therefore the velocity is expected to be dominated by the motion of the earth. Using the analytic approximation of Blandford &

Table 1: Observed quantities

Freq GHz	date 1999	MJD (start)	rms/60s mJy	$< S >$ mJy	m	σ_m	m$'$	t mins	σ_t	$\sigma_{\delta f}$
1.340–1.380	May 13-14	51311	1.4	81	0.13	0.02	0.24	212	12	0.03
1.340–1.420	May 13-17	51311	1.0	87	0.12	0.02	0.21	–	–	–
2.210–2.290	May 13-17	51311	1.0	95	0.24	0.04	0.44	–	–	–
4.834–4.874	May 13-14	51311	2.8	146	0.29	0.01	0.52	34	4	0.17
4.834–4.914	May 14-15	51312	2.0	125	0.32	0.03	0.58	32	2	0.05
8.450–8.490	May 14-15	51312	2.5	208	0.21	0.01	0.38	30	6	0.10

m : modulation index, or the normalised rms fluctuations in intensity

m$'$: modulation index with 55% of the flux density in the scintillating component

t : timescale for the variations. Error on timescale σ_t determined by omitting $\sigma_{\delta f}$ correction

Narayan (1985), for a Kolmogorov spectrum of irregularities in a thin screen, we solve:

$$\Theta_{\mu as} = 0.012 v_{kms^{-1}} t_{hrs} L_{kpc}^{-1}$$

$$C_{-4} = 22.4 \Theta_{\mu as}^{5/3} \lambda_{cm}^{-11/3} L_{kpc}^{-1}$$

$$\lambda_{cm}^{crit} = 2.77 C_{-4}^{-6/17} L^{-11/17}$$

Taking the critical wavelength λ^{crit}=6 ± 1.5cm, v=50 km s^{-1} and t=0.5 hrs we obtain C$_N^2$=0.17±0.05m$^{-20/3}$, an effective distance to the scattering screen of 19^{-4}_{+6} pc, and a source radius of $16 \pm 4\mu$arcsec. We note that this theory is only strictly valid in the weak scattering regime, but that the source size and distance so derived agrees well with the more simple derivation above.

The 5 GHz light curve is repeatedly seen to drop to values as low as 60 mJy. The consistency of the 'base-level' provides evidence for a non-scintillating (larger) component and provides a strong constraint of $\leqslant$ 60 mJy in this component (and implies $\geqslant$ 75 mJy in the scintillating component, taking 135 mJy as the average flux density). Fig. 3 shows the observed m, and the curves obtained with the maximum possible flux density in the extended material, and the scintillating component as smaller than the scattering disk.

We considered the case that all the source flux density is contained in a region somewhat larger than Θ, allowing the source size to vary as a negative power of frequency. In order to reproduce the fluctuation indices observed, the source cannot be more than ~10 times the Fresnel scale at the critical frequency. However, the very rapid variations at 5 GHz then require an extremely strong scattering screen (C$_N^2$ ~ 10^{4}m$^{-20/3}$) less than a parsec distant. As there is no evidence for such material (e.g. from pulsar studies), we do not subscribe to such a model.

We have searched for (even faster) diffractive scintillation in observations with a bandwidth of 5 MHz at 1.38 GHz, but found none (m$_{diff}$ < 0.1). However, interpretation of this as a source size is complicated by the unknown flux density of the non-scintillating component and the possibility that the decorrelation bandwidth may be <5MHz. Further, for sources with m$_{diff}$ < 1, the predicted diffractive timescale increases and becomes closer to the refractive one.

4. Discussion

J 1819+3845 must have at least 75 mJy within a radius 16 μarcsecs at 5 GHz, if 5 GHz is the critical frequency. This results in an observed brightness temperature T$_b$ > 5.10^{12}K. A higher critical frequency results in a higher brightness temperature for a flat or rising spectrum of the scintillating component.

The scattering occurs closer to the observer than is predicted by a uniform weighting of the TC93 model. A screen location at ~25 pc is, however, in agreement with the model of the Local Bubble by Bhat, Gupta & Rao (1997), to which the authors attributed enhanced scattering of pulsars. If the scattering occurs further away, a smaller source size and higher T$_b$ is required, although, as outlined above, this is difficult to reconcile with the data. We also point out that the contribution to the scattering of a source of finite size seen through an extended medium will be greatest where the Fresnel scale is equal to the angular size

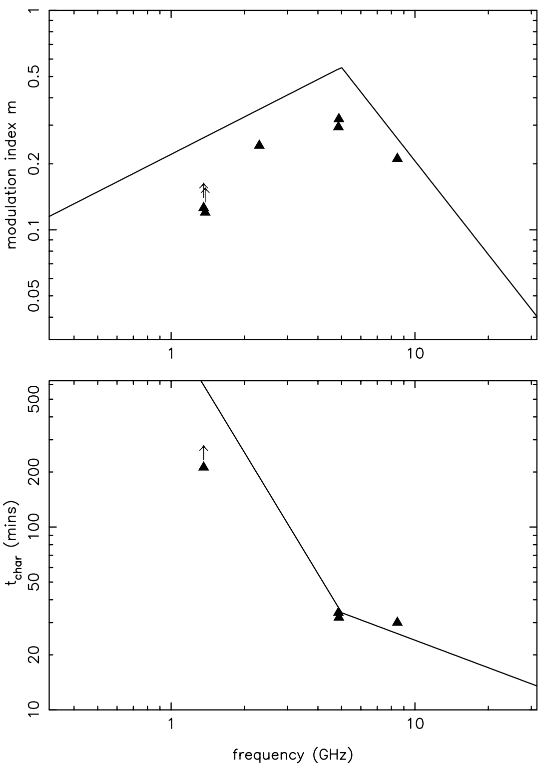


Fig. 3.— Observed modulation index and timescales overlaid on thin-scattering screen model predictions, for a scintillating component plus a non-scintillating region. There is 55% of the total flux density in the scintillating component at all frequencies. The critical frequency taken as 5 GHz where we take m=1 for a point source, and the predicted timescale is normalised to the timescale at 5 GHz.

of the source. This effect will decrease the distance of the effective scattering screen.

If we assume that the rising spectrum is caused by synchrotron self-absorption, from an isotropic particle distribution producing optically thin emission above ν_{obs}, we calculate that a Doppler factors ($\mathcal{D}$) of 12–15 are required to explain the apparent T$_b$. (We use the formula of Readhead (1994) and consider both the high frequency cut-off to be $10\times\nu_{obs}/\mathcal{D}$ and the canonical cut-off of 100GHz, with a particle energy index of 2, ν_{obs}=43 GHz). An obvious candidate for such emission is an optically thick component of an extremely fast, sub-parsec jet. This should be moving at $\sim$ 1 mas per year: readily detectable by VLBI.

However, such an object is suffering large Compton losses, and will survive much less than a year, without input of fresh energy. In the observer's frame, the half-life of the electrons emitting at the peak frequency is only a couple of light weeks, due to time dilation. Such effects cannot be avoided by a faster moving blob, as the effect of time dilation increases faster than the increase in energy loss timescale. This energy loss is apparently not seen: average 5 GHz flux densities in January, March and May 1999 are 123, 135, and 135 mJy respectively. J 1819+3845 is also apparently stable in the long term: the available data at all frequencies spans over 10 years, and show no changes greater than a factor of 2 (fig.1).

We cannot yet rule out that the source may be 'transient' and radiating above the Compton limit for a period no longer than the light-crossing time of the source, after a single injection of energy. However, the remarkable fact that the source showed the same modulation index (flux density range of a factor 3) over a period of at least 2, probably 4, months suggests to us that the emission comes from a steady region in space through which emitting particles flow. We suggest two broad pictures, both of which require a continuous internal source of energy:

(a) a 'cauldron' near the AGN, of which we see the $\tau \approx 1$ surface. The particles are continuously regenerated near the black hole and lose energy exceedingly rapidly.

(b) a relativistic wind of particles or jet in which the particles stream out. Under these conditions inverse Compton losses may be seriously reduced (e.g. Woltjer 1966)

PKS 0405-385 is also an inverted spectrum quasar (Kedziora-Chudczer et al 1997) as is PKS 1741-038 whose variations have also been interpreted as scintillation (Hjellming & Narayan 1986). We suggest that the unusual spectral shape is an important feature. The overall shape and relative stability of the radio spectrum (0.3 – 43 GHz) is also reminiscent of that of M81 (de Bruyn et al, 1976; Reuter and Lesch, 1996) as well as SgrA* (Falcke et al, 1998).

5. Conclusions

The combination of exceedingly large modulations in the received flux density and its very short variability timescales make the quasar J 1819+3845 the most extremely variable source known in the radio sky. At 5 GHz its modulation timescale is half an hour, and the peak to peak variations are frequently 350%. We interpret the variations as due to interstellar scintillation, and derive an angular diameter at 5 GHz of $<32\,\mu$arcsecs.

The apparent brightness temperature is $> 5.10^{12}$K. Unlike the 'variability' T_b observed in IDVs, this is (almost) a direct measurement. The source J 1819+3845 is at most five light-months in diameter. Considering the object as a plasma blob, isotropically emitting in its rest frame, requires bulk relativistic motion with $\mathcal{D}{\sim}15$ to explain the observed brightness temperature. However, the inverse Compton energy loss timescales for such an object are a few weeks, but we have seen similar mean flux densities and scintillation over 4 months. We favour models in which energy is supplied continuously to the emitting region, and we are observing a 'constant surface' of the source through which particles flow.

A very high T_b (10^{14}K) was derived for another quasar PKS 0405-385, whose variability was also interpreted as an effect of scintillation (Kedziora-Chudczer et al 1997). Such a high brightness temperature would not be needed if the effective scattering screen was placed closer to the observer than assumed by Kedziora-Chudczer et al. The interpretation of IDV variations as intrinsic implies source sizes which are often small enough for scintillation to play a role (Rickett et al 1995). Good evidence for scintillation in two sources strengthens the case that IDV variations are predominantly caused by scintillation effects.

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REFERENCES

Aller, H. D., Aller, M. F., Latimer, G. E. & Hodge, P. E. 1985, ApJS, 59, 513

Armstrong, J. W. & Rickett, B. J. 1981, MNRAS, 194, 623

Bhat, N. D. Ramesh, Gupta, Yashwant & Rao, A. Pramesh 1998, ApJ, 500, 262

Blandford, R. & Narayan, R. 1985, MNRAS, 213, 591

Bruyn, A. G. de, Crane, P. C., Price, R. M. & Carlson, J. B. 1976, A&A, 46, 243

Falcke, H. , Goss, W. M., Matsuo, H. , Teuben, P. , Zhao, J. -H. & Zylka, R. 1998, ApJ, 499, 731

Hjellming, R. M. & Narayan, R. 1986, ApJ, 310, 768

Kedziora-Chudczer, L., Jauncey, D. L., Wieringa, M. H., Walker, M. A., Nicolson, G. D., Reynolds, J. E. & Tzioumis, A. K. 1997, ApJ, 490, L9

Myers, S. et al, 1999, in prep.

Narayan, R. 1992, Phil. Trans. R. Soc. Lond., 341, 151

Readhead, A. C. S. 1994, ApJ, 426, 51

Rickett, B. J. 1977, ARA&A, 15, 479

Rickett, B. J., Coles, W. A. & Bourgois, G. 1984, A&A, 134, 390

Rickett, B. J. 1986, ApJ, 307,

Rickett., A., Quirrenbach, B. J., Wegner, R., Krichbaum, T. P. & Witzel, A. 1995, A&A, 293, 479

Reuter, H. -P. & Lesch, H. 1996, A&A, 310, L5

Simonetti, J. H., Cordes, J. M. & Heeschen, D. S. 1985, ApJ, 296, 46

Taylor, J. H. & Cordes, J. M. 1993, ApJ, 411, 674

Vermeulen, R. C. & Cohen, M. H. 1994, ApJ, 430, 467

Wagner, S. J. & Witzel, A. 1995, ARA&A, 33, 163

Walker, M. A. 1998, MNRAS, 294, 307

Witzel, A., Heeschen, D. S., Schalinski, C. & Krichbaum, T. 1986, Mitteilungen der Astronomischen Gesellschaft Hamburg, 65, 239

Woltjer, L. 1966, ApJ, 146, 597

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