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# Emergence and disappearance of microarcsecond structure in the scintillating quasar J1819+3845

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## ABSTRACT

The 4.8-GHz light curves of the scintillating intraday variable quasar J1819+3845 during 2004–2005 exhibit sharp structure, down to a time-scale of 15 min, that was absent from light curves taken prior to this period and from the 2006 light curves. Analysis of the light curve power spectra show that the variations must be due to the emergence of new structure in the source. The power spectra yield a scattering screen distance of 3.8 ± 0.3 pc for a best-fitting $v_{\rm ISS} = 59 \pm 0.5\,{\rm km\,s^{-1}}$ or 2.0 ± 0.3 pc for the scintillation velocity reported by Dennett-Thorpe & de Bruyn. The scattering medium is required to be exceptionally turbulent, with $C_N^2 \gtrsim 0.7\,\Delta L_{\rm pc}^{-1}\,{\rm m}^{-20/3}$ for scattering material of thickness $\Delta L_{\rm pc}$ pc along the ray path. The 2004 power spectrum can be explained in terms of a double source with a component separation 240 ± 15 μas in 2004.

**Key words:** techniques: high angular resolution – scattering – galaxies: active – quasars: individual: J1819+3845.

## 1 INTRODUCTION

The quasar J1819+3845 exhibits 20–35 per cent rms intensity modulations on intrahour time-scales at centimetre wavelengths. The variations are due to interstellar scintillation caused by plasma thought to be located only $z = 4$–12 pc from Earth (Dennett-Thorpe & de Bruyn 2002, 2003, hereafter DB03). For $z = 10$ pc the ∼30 min scintillations observed in the period December to March each year imply an overall source size of ∼60 μas, corresponding to 0.39 pc at its redshift of 0.54 ($H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$).

The source has exhibited variations every time since they were first observed in 1999. This is surprising because it might be supposed that such a compact source, with a brightness temperature exceeding the inverse Compton limit, should expand and cease scintillation after several months. This problem is common to several persistent extreme intraday variable sources including PKS 1519−273 and PKS 1257−326 (Macquart et al. 2000; Bignall et al. 2003). At the very least, one would expect such compact sources to exhibit some degree of structural variability, made evident by changes in the variability characteristics.

The detection of structural changes in intrahour variable sources is complicated, however, by annual cycles in their variability time-scale (DB03; Bignall et al. 2003). Both the amplitude and direction of the scintillation velocity change as the Earth's velocity changes relative to the scattering medium as it orbits the Sun. This changes the scintillation direction, which in turn alters the character of the scintillations (i.e. its power spectrum) if the turbulence in the scattering medium is anisotropic or if the source structure is asymmetric. Both asymmetries hinder searches for structural variability. These asymmetries are particularly important for J1819+3845 because its scintillation pattern is anisotropic, with an axial ratio of $15^{+>30}_{-8}$ (DB03).

In this Letter we identify the emergence of a new structure within J1819+3845 at λ6 cm by comparing observations taken at identical epochs each year, thus removing ambiguity introduced by the annual cycle between intrinsic source structural evolution and asymmetry in the scintillation pattern. In Section 2 we present the light curves indicating the emergence of this new structure. In Section 3 the light curve power spectra are analysed to deduce its properties. The implications of the discovery are summarized in Section 4.

## 2 OBSERVATIONS

Fig. 1 shows the light curves from observations made over six epochs in the period 2000–2006 at 4.8 GHz with the Westerbork Synthesis Radio Telescope. Details of the data reduction procedure are described in DB03. Each observation was made at the same time each year so that the scintillation velocity vector is identical on all occasions; no light curves during the period 2001–2002 are shown because we do not have good quality light curves near the pertinent dates.

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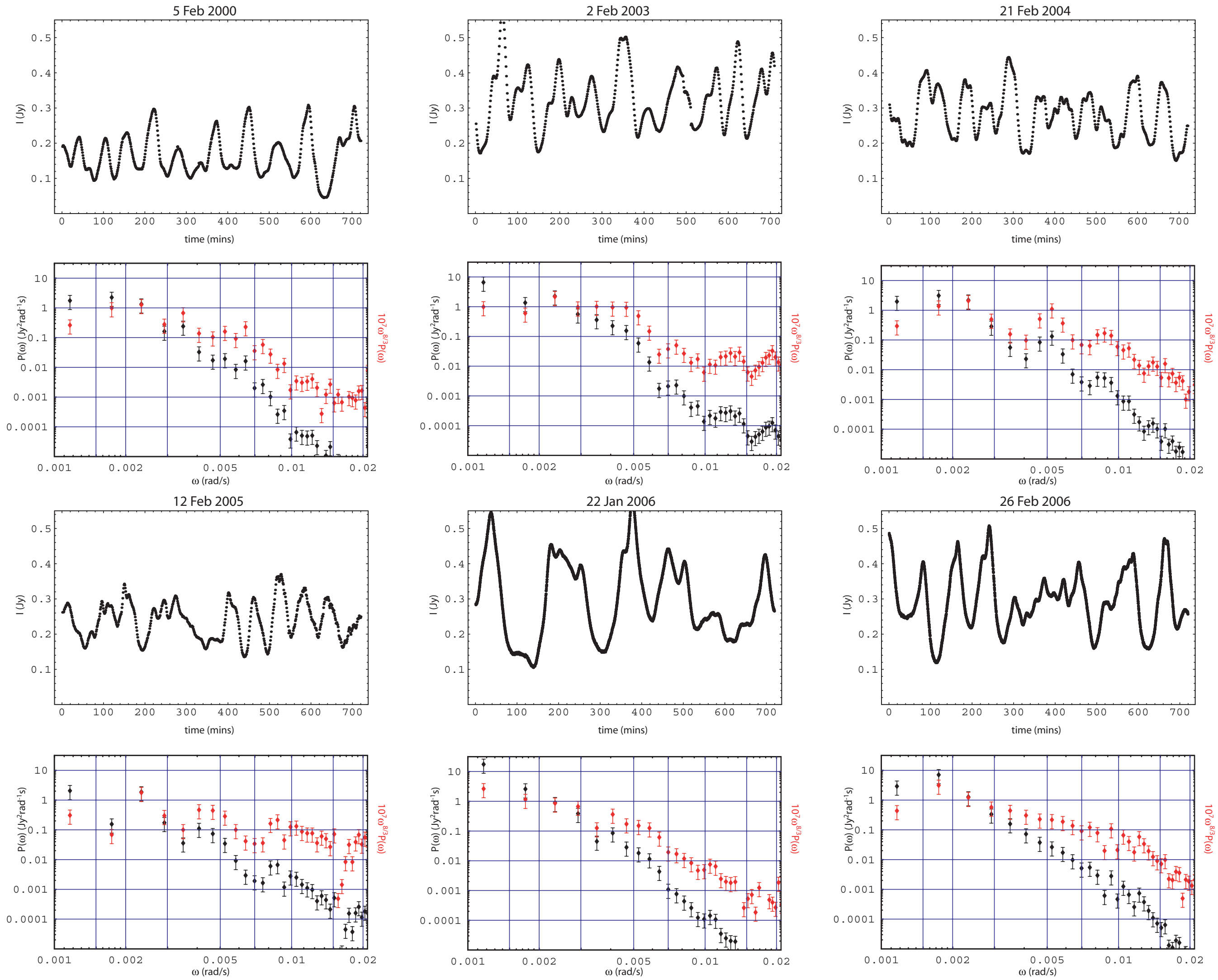


**Figure 1.** The μas structural evolution of J1819+3845, demonstrated by changes in character of the light curves and their associated spectra (black points). The red points show the power spectra weighted by $\omega^{8/3}$ (see text for details). The spectra were pre-whitened to prevent leakage of low-frequency power associated with the time-sampling window function to high frequencies. A noise bias, determined from the spectral power near 0.1 rad $s^{-1}$, is also subtracted from the spectra (see Macquart & de Bruyn 2006). To reduce the errors, at the expense of information at low $\omega$, each spectrum shown is the average obtained by computing separate spectra for each 3-h block of data within each 12-h light curve. The error on each point is half of its mean value and follows a $\chi^2$ distribution with 8 degrees of freedom. It would be appropriate to normalize spectra by the source mean flux density if the entire source were subject to scintillation, but as this is not necessarily the case and it is misleading otherwise, the plots here are not so normalized. The 2000–2005 light curves were observed with 60 s time-resolution while the 2006 light curves were observed with 10 s resolution. The source mean flux was around 300 mJy over 2003–2006 after a fast rise from 125 to 300 mJy between 2000 and 2003.

The light curves exhibit an increase in the degree of small time-scale structure in 2004–2005 compared to those spanning the interval 2000–2003. The power spectra of the variations develop substantial structure at angular frequencies between 0.005 and 0.02 rad $s^{-1}$, and peak-to-peak variations shorter than 15 min (corresponding to structure on a time-scale ≈4 min in the structure function) are observed in the 2004–2005 light curves. This corresponds to the highly significant $\omega \approx 0.005$ rad $s^{-1}$ bumps evident in the 2004–2005 power spectra. An additional feature at $\omega \approx 0.008$ rad $s^{-1}$ is also evident, albeit at a low power, in the 2005 spectrum. Both these bumps are either absent or less evident in the 2000–2003 and 2006 spectra, although several do possess a significant 'knee' near 0.004 rad $s^{-1}$.

Analysis of similar power spectra taken on calibrator sources allow us to be confident that the power spectrum is not dominated by telescope noise and systematic effects down to angular frequencies $\omega \approx 0.015$ rad $s^{-1}$ (see Macquart & de Bruyn 2006). Another set of observations taken on 26–31 March over the period 2001–2006 (see Fig. 2 for a comparison between March 2004–2005 variations with the 21 February 2004 variations) shows a similar recent increase in the amount of small scale structure in the light curves, but we shall concentrate on the analysis of the February data sets in this Letter.

## 3 SCINTILLATION MODELLING

The differences between the character of the light curves over the interval 2000–2006 can be interpreted either in terms of (i) changes in the interstellar turbulence responsible for the scintillations observed in J1819+3845, or (ii) changes in the internal structure of the quasar.

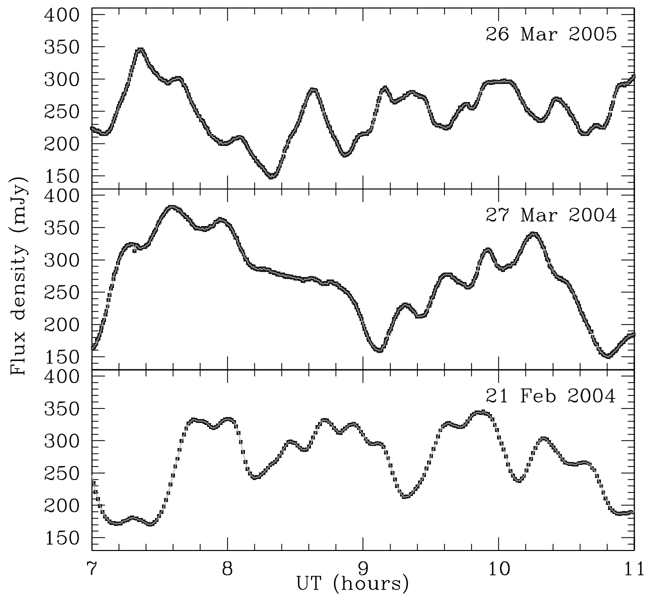


**Figure 2.** Light curves of J1819+3845 at 4.8 GHz taken during February and March 2004/5. The February data have 60 s sampling, the other two 30 s.

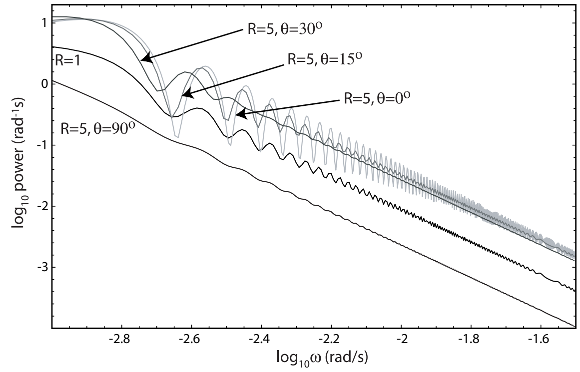


**Figure 3.** Scintillation power spectra for a point source of unit flux density with $v_{\rm ISS} = 50\,{\rm km\,s^{-1}}$ and $z = 10$ pc for various $R$ and $\theta$.

This is illustrated by the expression for the power spectrum of temporal variations in the regime of weak scintillation, applicable to the variations of this source at $\lambda$ 6 cm (Codona & Frehlich 1987; Dennett-Thorpe & de Bruyn 2000):

$$P(\omega) = \frac{1}{v_{\rm ISS}} \int_{-\infty}^{\infty} {\rm d}q_y \, P_{\rm pt}\left(\frac{\omega}{v_{\rm ISS}}, q_y\right) \left| V\left(\frac{\omega z}{v_{\rm ISS} k}, \frac{q_y z}{k}\right)\right|^2, \qquad (1)$$

where $V(\boldsymbol{r})$ is the source visibility measured on a baseline $\boldsymbol{r}$, $k = 2\pi/\lambda$ is the wavenumber, $\boldsymbol{v}_{\rm ISS}$ is the scintillation velocity, here oriented along the $x$-axis, and

$$P_{\rm pt}(\boldsymbol{q}) = 8\pi r_{\rm e}^2 \lambda^2 \Phi_{N_{\rm e}}(\boldsymbol{q}) \sin^2\left(\frac{q^2 z}{2k}\right) \qquad (2)$$

is the spatial power spectrum of intensity scintillations that would be observed if the source were point-like. The amplitude of the line-of-sight-integrated electron density power spectrum $\Phi_{N_{\rm e}}$, for turbulence located on a thin screen of thickness $\Delta L$ at a distance $z$, is scattering measure ${\rm SM} = C_N^2 \Delta L$. The scintillations are likely to emanate from only a single thin scattering screen because only a single screen velocity is required to model the annual cycle in the scintillation time-scale (DB03).

Changes in the turbulence spectrum are disfavoured as the cause of changes in the variability characteristics because they require a rather contrived modification of the power spectrum over only a narrow spatial wavenumber range. The appearance of spectral features over the frequency range $\omega \approx (4\text{–}10) \times 10^{-3}\,{\rm rad\,s^{-1}}$ requires an enhancement of power in the electron density power spectrum only over wavelengths $2\,\pi\, v_{\rm ISS}/\omega \approx (3\text{–}8) \times 10^7\, v_{50}$ m (where $v_{50} \equiv v_{\rm ISS}/50\,{\rm km\,s^{-1}}$). Changes in the variability characteristics are more readily interpreted in terms of evolution in the μas source structure. Such evolution is expected as both the intrinsic flux density and polarization are observed to change in this source on $\gtrsim$0.5-yr time-scales.

The ~15-min variations in the 2004–2005 light curves require the presence of ultracompact structure within the source. However, the detailed shape of their power spectra depend on both the source structure and the scintillation physics. The peaks observed in the 2004–2005 power spectra could be due to either structure in the source visibility function or oscillations caused by the sine-squared term in equation (2), the ‘Fresnel filter’. The latter could become more prominent if the source becomes more compact. Oscillations due to the Fresnel filter are exacerbated when the turbulence is anisotropic, here parametrized by introducing an elongation, $R$, in the electron density spectrum, oriented at an angle $\theta$ to $\boldsymbol{v}_{\rm ISS}$:

$$\Phi_{N_{\rm e}} = {\rm SM}\left[\frac{(q_x \cos\theta + q_y \sin\theta)^2}{R} + R\,(q_x \sin\theta - q_y \cos\theta)^2\right]^{-\frac{\beta}{2}}. \qquad (3)$$

Fig. 3 shows the power spectrum for a point source for a variety of scattering geometries assuming the index for Kolmogorov turbulence of $\beta = 11/3$. Fresnel oscillations are potentially important in the interpretation of J1819+385 power spectra because its scintillation pattern is anisotropic.

It is difficult to attribute all the features of the 2004–2005 power spectra to Fresnel oscillations because the spectral peaks change positions between years (see, for example, the 4 mrad s$^{-1}$ feature in the 2004 spectrum). Even within a single power spectrum the locations of the peaks are inconsistent with a unique value of $r_{\rm F}$; numerical integration of equation (1) shows that no combination of $r_{\rm F}$ and $\theta$ reproduces the peak locations observed in the 2004–2005 spectra. None the less, detailed fitting described below suggests that the first peak, at 1.7 mrad s$^{-1}$, exhibited by many of the spectra, can indeed be attributed to the first peak of the Fresnel filter, and implies a screen distance $\sim$5 $v_{50}$ pc.

The inability of the Fresnel filter to account for the peaks in the 2004–2005 spectra leads us to consider the additional influence of source structure. We first discuss simple arguments to deduce general source properties from the power spectra before reproducing them quantitatively using a specific source model.

We examine the size of the structure implied by the fast variations evident in the 2004–2005 light curves. The scintillation power expected for a point source declines as $\omega^{-8/3}$ for $\omega \gtrsim 2.5 \times 10^{-3}$ rad s$^{-1}$ and $\beta = 11/3$ (viz. equation 1 and Fig. 3). For a point-like source the visibility, $V(\boldsymbol{r})$, and hence $\omega^{8/3}\,P(\omega)$, would be flat. Consider the $\omega^{8/3}$-weighted power spectra shown in red in Fig. 1. Fluctuations at $\omega$ depend on $|V(r \approx \omega r_{\rm F}^2/v_{\rm ISS})|$, so the frequency at which the red points depart from a flat line marks the point at which the source structure dominates the shape of the power spectrum. This yields a *rough* estimate of the source size. A sharp decline in $\omega^{8/3}P(\omega)$ at a scale $\omega_0$ indicates the presence of structure down to an approximate scale:

$$\Theta \sim 3.3 \left( \frac{\omega_0}{0.01\,\mathrm{rad\,s^{-1}}} \right)^{-1} \left( \frac{v_{\mathrm{ISS}}}{50\,\mathrm{km\,s^{-1}}} \right) \left( \frac{z}{10\mathrm{pc}} \right)^{-1} \mu\mathrm{as}. \qquad (4)$$

For instance, the 0.01 rad $\mathrm{s}^{-1}$ break in the 2006 February 26 power indicates structure down to $\sim 7\, v_{50}\, z_5^{-1}$ µas if the index of the turbulence spectrum is $\beta = 11/3$. If the turbulence spectrum were shallower there is less source structure at high angular resolution, and if steeper there is more.

Because the bumps in the power spectra cannot be reproduced in terms of Fresnel oscillations, we consider the simplest source model capable of introducing additional spectral peaks. A double source, with component flux densities $I_1$ and $I_2$ and sizes $\theta_1$ and $\theta_2$, with brightness power spectrum

$$|V(\boldsymbol{r})|^2 = I_1^2 \mathrm{e}^{-k^2 r^2 \theta_1^2} + I_2^2 \mathrm{e}^{-k^2 r^2 \theta_2^2} + 2 I_1 I_2 \mathrm{e}^{-k^2 r^2 (\theta_1^2 + \theta_2^2)/2} \cos(k \Delta\boldsymbol{\theta} \cdot \boldsymbol{r}), \qquad (5)$$

induces oscillations in the scintillation power spectrum whose spacing depends on the component separation, $\Delta\theta = \Delta\theta\,(\cos\alpha, \sin\alpha)$, where $\alpha$ is the angle the vector makes with $\boldsymbol{v}_{\mathrm{ISS}}$. The oscillations are partially damped if the mean square of the component angular sizes exceeds $\sim \Delta\theta$.

We performed fits to two power spectra up to $\omega = 0.015$ rad $\mathrm{s}^{-1}$, the point beyond which the power dips below the level at which we are able to confidently measure flux density variations. The 2006 February 26 spectrum, closely resembling the 2000–2003 spectra, was used as representative of spectra with the simpler structure, while the 2004 February 21 spectrum is representative of data in which additional fast, small-amplitude variations are prominent. The fit was performed to both spectra simultaneously to ensure the scattering parameters, SM, $z$, $R$, $v_{\mathrm{ISS}}$ and $\theta$, were common to both.

The best-fitting parameters are listed in Table 1. Double component models were fitted to both spectra. Fig. 4 shows that the models reproduce the essential characteristics of the power spectra well. Two models, M1 and M2, were fitted for. They differ in that $v_{\mathrm{ISS}}$ and $\alpha$ were fixed in M2 to values suggested by the annual cycle

**Table 1.** Fit parameters with $1\sigma$ errors for the 2004 and 2006 power spectra derived using the CERN MINUIT minimization package, which estimates errors based on the second derivatives of $\chi^2$. Fit parameters are defined in the text. Fitting models M1 and M2 differ only in that parameters marked by asterisks are held fixed in M2. The redshift-corrected brightness temperature of component 1 in M1 is $1 \times 10^{13}$ K.

| | M1 | | M2 | |
|---|---|---|---|---|
| Reduced $\chi^2$ | 39.1/39 d.o.f. =1.0 | | 45.8/42 d.o.f. = 1.1 | |
| Fit Parameter | | | | |
| SM ($10^{17}$ $\mathrm{m}^{-5.67}$) | $2.6 \pm 0.2$ | | $2.4 \pm 0.2$ | |
| $z$ (pc) | $3.8 \pm 0.3$ | | $2.0 \pm 0.3$ | |
| $v_{\mathrm{ISS}}$(km $\mathrm{s}^{-1}$) | $59.0 \pm 0.5$ | | 42.5* | |
| R | $2.9 \pm 1.0$ | | $1.9 \pm 0.6$ | |
| $\theta$ (rad) | $2.26 \pm 0.02$ | | $0.9 \pm 0.2$ | |
| | 2004 | | 2006 | |
| | M1 | M2 | M1 | M2 |
| $I_1$ (mJy) | $42 \pm 7$ | $69 \pm 30$ | $67 \pm 11$ | $100 \pm 45$ |
| $I_2$ (mJy) | $11 \pm 4$ | $9 \pm 4$ | $17 \pm 12$ | $25 \pm 13$ |
| $\Delta\theta$ (µas) | $240 \pm 15$ | $220 \pm 20$ | $565 \pm 15$ | $556 \pm 16$ |
| $\alpha$ (rad) | $0.00 \pm 0.03$ | 1.07* | $2.4 \pm 0.3$ | 1.07* |
| $\theta_1$ (µas) | $16 \pm 1$ | $18 \pm 2$ | $20 \pm 3$ | $26 \pm 4$ |
| $\theta_2$ (µas) | $16 \pm 2$ | $0 \pm 500$ | $7 \pm 4$ | $9 \pm 3$ |

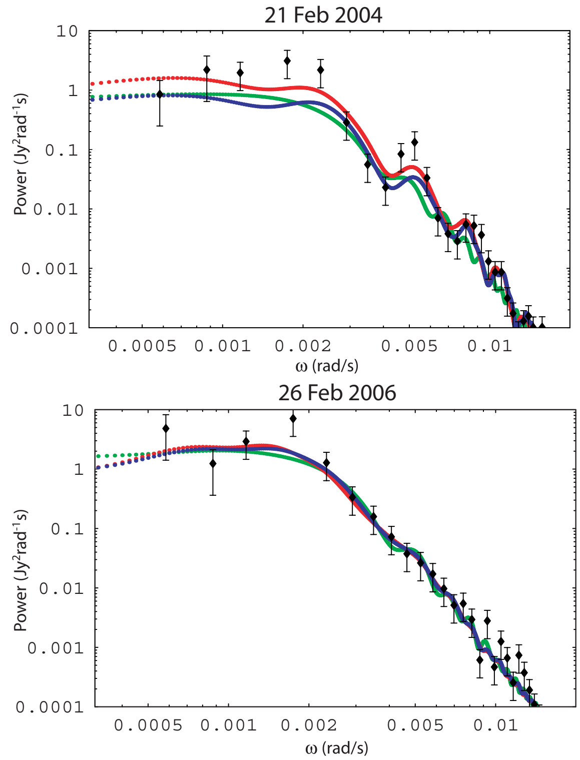


**Figure 4.** A fit to the 2004 February 21 and 2006 February 26 power spectra with the parameters of Table 1 (M1 blue line, M2 green line). The red line represents M1 but with $R = 3.5$. The higher anisotropy fit provides a better fit to the low-frequency part of the 2004 spectrum, but a worse fit overall with a reduced $\chi^2$ of 1.3 versus 1.0.

in the variability time-scale of the source (DB03). In fixing $\alpha$ instead of $\theta$ we assume that the source structure, rather than anisotropy in the turbulent scattering plasma, dominates the anisotropy of the source's scintillation pattern. This is justified by the low value of $R$ derived in all fits (see below). However, we caution that the large anisotropy of the scintillation pattern renders the solutions for $v_{\mathrm{ISS}}$ and $\alpha$ degenerate in the annual cycle fit described in DB03. Thus it is not clear that the 'best-fitting' parameters suggested in DB03 do indeed represent the correct solution.

The quality of the fit was degraded by fitting the spectra with a single source component. However, we note that the best-fitting flux density of the second component is only 2–3$\sigma$ from zero. A fit without the second component in the 2006 data yields a reduced $\chi^2$ of 1.2. The double-component model considered here is none the less strongly justified by polarization observations: time-delays are observed between the polarized and unpolarized variations of this source over the entire period 2000–2006, demonstrating that the source always comprises at least two components, one of which is likely highly polarized (Macquart, de Bruyn & Dennett-Thorpe 2003). There was no improvement in the fit quality by allowing $\beta$ to vary from its assumed value of 11/3; the reduced $\chi^2$ for the fit was 1.02 and yielded $\beta = 3.87$. However, other possible islands of low $\chi^2$ conceivably exist besides those detected by our fitting program and may yield acceptable fits with values of $\beta \sim 5$.

The $R = 2.9 \pm 1.0$ turbulence anisotropy derived from the fit is smaller than the $15^{+>30}_{-8}$ anisotropy of the scintillation pattern itself (DB03), but is not inconsistent because the latter is also influenced by asymmetry in the source structure. The value of $R$ is particularly sensitive to the low-frequency portion of the power spectrum. Two low-frequency points, obtained by recomputing the power spectrum from the light curves subdivided into 6 h blocks, were therefore added to the spectra employed in the fitting (see Fig. 4). This additional information is obtained at the expense of poorer error estimates associated with these points. The derived anisotropy ratio should therefore be regarded with some caution; we expect to derive a better estimate in future from longer duration observations.

There is a degeneracy between SM and the component flux densities; only the product SM $I^2$ affects the spectral amplitude. As the sum of the component flux densities cannot exceed the 281- and 295-mJy mean flux densities observed in the 2004 and 2006 light curves, respectively, the highest possible values of $I_1$ and $I_2$ in the 2006 spectrum in M1 are 236 mJy and 60 mJy, respectively, requiring SM $> 2.1 \times 10^{16}\,\mathrm{m}^{-17/3}$. This places a lower bound on the turbulent amplitude of $C_N^2 > 0.68\,(\Delta L/1\,\mathrm{pc})^{-1}\,\mathrm{m}^{-20/3}$. For comparison, Macquart & de Bruyn (2006) deduced SM = (1–1.4) $\times$ $10^{17}\,\mathrm{m}^{-17/3}$ for $z = 4$ pc in a fit to the refractive scintillation at 1.4 GHz. A Virginia Tech Spectral-Line survey measurement (see http://www.phys.vt.edu/~halpha/) of the H$\alpha$ intensity at the position of J1819+3845 implies SM $= 1.1 \times 10^{17} T_4^{0.9} l_0^{-2/3} \epsilon^2/(1+\epsilon^2)\,\mathrm{m}^{-17/3}$, where the gas temperature is $T = 10^4\, T_4$ K, $l_0$ is the turbulence outer scale in au and $\epsilon^2 = \langle(\delta n_e)^2\rangle/\bar{n}_e{}^2$ is the normalized electron density variance. This suggests $l_0 \lesssim 9$ au if $\epsilon \sim 1$ and $T_4 \lesssim 10$.

A weaker degeneracy between the screen distance and component angular sizes allows decreases in $z$ accompanied by corresponding increases in all measured angular sizes to yield fits of *similar* quality. However, changes in $z$ do adversely affect the fit because they also alter the positions of the Fresnel oscillations.

## 4 CONCLUSION

During 2004–2005 fast (~15-min) variations emerged over the ~30-min variations normally observed in the light curve of the scintillating quasar J1819+3845. In 2006 the source reverted to variations similar to those in 2000–2003. The changes are best explained in terms of evolution in the source structure. A double-component source is capable of explaining the power spectra during 2004–2005. The spectral peak at $\omega \approx 2 \times 10^{-3}\,\mathrm{rad\,s}^{-1}$ corresponding to the large amplitude, slow variations and visible in all spectra, is explained by oscillations of the 'Fresnel filter', from which a $\sim 5\, v_{50}$ pc distance to the scattering medium is deduced. Holding the scintillation velocity fixed at the value derived by DB03 yields $z = 2.0 \pm 0.3$, while fitting also for $v_{\rm ISS}$ yields $3.8 \pm 0.3$ pc. The fast variations in 2004–2005 are best attributed to oscillations in the source visibility function caused by a double-source structure with a component separation of $240 \pm 15$ μas in 2004. From a fit to the 2006 spectrum one infers a separation of $565 \pm 15$ μas. This implies an apparent expansion speed of $3.4 \pm 0.3\,c$ over the two years separating the two observations. However, we caution that it is also possible to fit the 2006 spectrum with a single component, in which case no expansion speed can be derived.

The emergence of these fast variations preceded other changes in the source, namely an increase in the modulation index and then the intrinsic flux density. The appearance of new structure may be connected with the diffractive scintillation reported at 21 cm (Macquart & de Bruyn 2006), but as absolute astrometry is not possible using scintillation techniques one cannot determine the angular offset between the components responsible for 6- and 21-cm variations.

The proximity of the scattering screen and the large amplitude of the intensity variations requires the scattering turbulence to possess an amplitude $C_N^2 > 1.7\,\mathrm{m}^{-20/3}$ if localized to a region of thickness no more than 0.4 pc, 10 per cent of its distance. This exceeds $C_N^2$ values deduced from most scattered pulsars (Cordes et al. 1988) by over two orders of magnitude.

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