A 3 Year Long Extreme Scattering Event in the Direction of the Millisecond Pulsar J1643–1224

V. Maitia, Jean-Francois Lestrade, Ismaël Cognard

The Astrophysical Journal, 582:972–977, 2003 January 10

A 3 YEAR LONG EXTREME SCATTERING EVENT IN THE DIRECTION OF THE MILLISECOND PULSAR J1643−1224

V. Maitia and J.-F. Lestrade
Observatoire de Paris Laboratoire d'Etude du Rayonnement de la Matière en Astrophysique, Centre National de la Recherche Scientifique, 77 avenue Denfert Rochereau, F-75014 Paris, France

and

I. Cognard
Laboratoire de Physique et Chimie de l'Environnement, Centre National de la Recherche Scientifique, 3A avenue de la Recherche Scientifique, F-45071 Orleans, France
Received 2001 July 9; accepted 2002 September 20

ABSTRACT

An extreme scattering event (ESE) has been detected in the direction of the millisecond pulsar J1643−1224 at 1.28 and 1.41 GHz. Its duration is 3 years and this makes it the longest ESE ever recorded. We have used the standard model of a purely refractive lens to interpret the observed radio light curves. This lens is a fully ionized cloud crossing the line of sight. We have found that our data imply that its transverse size is 56 AU, which is much larger than ∼1 AU typical of the other ESEs in the direction of the pulsar B1937+21. If the cloud is located at the mid-distance to J1643−1224 (2500 pc), its electron density is 130 e cm^{-3}. Such a highly pressurized structure has a short lifetime (29 yr), and this requires a replenishment mechanism at work in the interstellar medium that is unidentified at present. Alternative models are filamentary clouds seen through their long axis or a cold molecular hydrogen cloud with an ionized shell, as proposed by Walker & Wardle.

Subject headings: ISM: general — pulsars: individual (PSR J1643−1224) — scattering

1. INTRODUCTION

Radio observations of pulsars—dynamic spectra, pulse and angular broadening, dispersion measure (DM), rotation measure, and flux density fluctuations—indicate that the electron density in the local ionized interstellar medium (<1 kpc) has inhomogeneities well described by a Kolmogorov power spectrum at least in the wavenumber range of 10^{-13} m^{-1} < wavenumber < 10^{-8} m^{-1} (Armstrong, Rickett, & Spangler 1995). The standard interpretation of extreme scattering events (ESE) is that this ionized interstellar medium is permeated with discrete clouds of plasma (Fiedler et al. 1987; Romani, Blandford, & Cordes 1987). These rare events (ESE) are recognizable by a distinct signature in the radio light curve of a source when such a discrete cloud crosses the line of sight and produces a lens effect. ESEs have been detected in the directions of several quasars and of the pulsar B1937+21. The most recent census indicates that 15 ESEs have been identified in the radio light curves of 12 quasars in the entire Green Bank interferometer monitoring of 149 radio sources between 1979 and 1996 (Lazio et al. 2001). Five ESEs have been identified in the direction of the pulsar B1937+21 between 1989 and 1996 (Cognard & Lestrade 1996; Lestrade, Rickett, & Cognard 1998).

There are two models for discrete clouds working as lenses. First, Fiedler et al. (1994) propose a stochastic broadening model in which a plasma cloud is internally turbulent and scatters the flux density of the background source. Angular broadening of radio sources and pulse broadening of pulsars are expected in this model. Second, Romani et al. (1987) and Clegg, Fey, & Lazio (1998) study a purely refractive lens with a Gaussian profile for the electronic column density through which ray bundles of the background source are defocused in the middle of the ESE and are refocused at egress and ingress. Position changes and image splitting of radio sources as well as systematic delay in times of arrival of pulsars are expected in this model. Lazio et al. (2000) analyze VLBI observations of the extragalactic source PKS 1741−038 and show that the source image is angularly broadened during an ESE but not as much as the depth of the light curve would predict. They conclude that the lens is likely a mixture of these two effects: refractive defocusing and stochastic broadening. Cognard et al. (1993) examine flux density and timing variation during an ESE in the direction of the pulsar B1937+21. They found no pulse broadening but a systematic variation in the flux density and times of arrival that can be modeled with a purely refractive lens. However, as shown in Lazio et al. (2000), the lack of stochastic pulse broadening at frequencies larger than 1 GHz is not a stringent constraint.

An alternative to the standard model for ESEs has been proposed by Walker & Wardle (1998). In their theory, cold molecular hydrogen clouds are ionized superficially by the UV-radiation field in the Galaxy. The resulting ionized shell would form a purely refractive plasma lens responsible for ESEs. Such a cloud would be self-gravitating and at equilibrium, implying a long lifetime. The shell-like ionized structure in this model would be highly symmetric, and this would be clearly apparent in the shape of the radio light curve during an ESE.

Although distinct from the ionized phase of the interstellar medium relevant to our study, we point out that the cold neutral medium is similarly permeated with ubiquitous small-scale structures detected by VLBI (Faison et al. 1998) and by 21 cm absorption variations against high-velocity pulsars (Frail et al. 1994) as well as spectroscopy towards high-velocity stars (Welty & Fitzpatrick 2001). These discrete structures are cold atomic gas with a transverse length scale of a few AU and have a density of $\sim 10^5$ atoms cm^{-3}. Heiles (1997) studies the physical conditions required for equilibrium between the standard cold neutral medium and these small scales and suggests that filaments or sheets with an aspect ratio between 4 and 10 are required.

We present in this paper the observations of a new extreme scattering event (ESE) observed at 1.28 and 1.41 GHz at Nançay in the direction of the pulsar J1643−1224 that is remarkable for its duration of 3 years. We discuss the consistency of our observations with the two current models for ESEs (fully ionized clouds and cold H_2 clouds).

2. OBSERVATIONS OF THE PULSAR J1643−1224

The millisecond binary pulsar J1643−1224 discovered by Lorimer et al. (1995), at Galactic longitude $b = 5\overset{\circ}{.}67$ and latitude $l = 21\overset{\circ}{.}22$, is characterized by its proper motion 8 ± 5 mas yr^{-1} and distance $d = 4.9$ kpc (Toscano et al. 1999), rotation period $P_{\rm rot} = 4.622$ ms, DM = 62.4 pc cm^{-3}, and orbital period $P_b = 147$ days. We observed J1643−1224 at 1.28 and 1.41 GHz (left-circular polarization [LCP], right-circular polarization [RCP]) at the Nançay (France) decimetric radiotelescope from 1996 March to 1999 October, as frequently as 10–12 times per month. Each observation was about 60 minutes long over a bandwidth of 12 MHz. The integration of the dedispersed pulsar signal over the time-frequency domain was carried out with the swept frequency oscillator and autocorrelator of the station as described in Lestrade et al. (1998).

The calibration of our flux density series is based on standard procedures using system temperature and antenna sensitivity monitored by routine observations of standard flux density calibrators at Nançay. The flux density measurement is accurate to within 15% on an absolute scale. Diffractive speckles for J1643−1224 ($\Delta\nu_{\rm diff} \sim 0.5$ MHz and $\Delta t_{\rm diff} = r_{\rm diff}/v_{\rm trans} \sim 100$ s; Goodman & Narayan 1985; Stinebring et al. 2000) are largely averaged over our integration domain ($\Delta T \sim 60$ minutes, $\Delta\nu \sim 12$ MHz). The complete radio light curves we have measured at 1.28 and 1.41 GHz at Nançay from 1996 February to 1999 October are shown in Figures 1 and 2. The radiotelescope stopped in 1999 October for a major upgrade and the observations could not be pursued. The LCP and RCP flux densities have been averaged for each daily observation in Figures 1 and 2. These plots show the flux density of the pulse peak rather than the mean pulsar flux density. The uncertainty of the flux density is based only on the signal-to-noise ratio of each observation and does not include the possible 15% bias of the absolute scale since we are only interested in the variation of the light curve in our analysis.

The radio light curve exhibits a deep and rounded minimum ($\sim$40% of the initial flux density) bracketed by enhancements at both 1.28 and 1.41 GHz. Stinebring et al. (2000) have shown that there is no evidence for intrinsic long-term variability of pulsars above the 5% level after monitoring 21 pulsars for 5 yr. We argue that the systematic variation observed is typical of ESEs despite the lack of scintillation data well before and after the event that would be informative. First, the radio light curve of J1643−1224 (DM = 62.4 pc cm^{-3}) can be compared to the flux density variations of other pulsars with similar DMs. Lestrade et al. (1998) report 8 years of observations of B1937+21 with DM = 71 pc cm^{-3} at 1.4 and 1.7 GHz at Nançay. Scintillation with short decorrelation timescale of $\sim$10 days is apparent for B1937+21 outside the five periods during which ESEs have been identified (see their Fig. 2). Also, Stinebring et al. (2000) present light curves for B0531+21 (DM = 57 pc cm^{-3}), B0833−45 (DM = 69 pc cm^{-3}), and B1556−144 (DM = 59 pc cm^{-3}) at 610 MHz that show no smooth variations on a timescale greater than 6 months as seen with J1643−1224. In addition, scintillation for these pulsars observed at 610 MHz is never deeper than 20% of the mean flux density, and this would be $\sim$13% at 1.4 GHz allowing for the frequency dependence ($\sqrt{\nu}$). This is in contrast to the 40% drop found for J1643−1224. Following Fieldler et al. (1994) for ESEs in directions of quasars, we compute the amplitude variation ψ and the timescale of the event τ for J1643−1224. The amplitude variation $\psi = (F_{\rm max} - F_Q)/(F_Q - F_{\rm min}) = (68 - 55)/(55 - 35) = 0.65$ is computed with the flux densities at maximum, minimum, and quiescence ($F_{\rm max}$, $F_{\rm min}$, and F_Q; values in the formula are in units of mJy). The timescale of the event $\tau = \tau_{\rm FW}/\tau_{\rm FWHM} = 3/1 = 3$ is computed with the total duration $\tau_{\rm FW}$ and duration $\tau_{\rm FWHM}$ when the flux density is at the midpoint between $F_{\rm max}$ and $F_{\rm min}$ (values in the formula are in units of years). These values found for the pulsar J1643−1224 are fairly consistent with the ranges of values found for quasars at 2.7 GHz; $0.3 < \psi < 2.0$ and $1.2 < \tau < 2.5$ (Fiedler et al. 1994). Finally, the degree of symmetry for the event in the direction of J1643−1224 is striking, and this property is frequently found by Fiedler et al. (1994).

The standard interpretation is stochastic broadening (Fiedler et al. 1987) or refractive defocusing (Romani et al. 1987) by an isolated structure fully ionized and crossing the line of sight. The whole event in the direction of J1643−1224 lasted about 3 yr, and this is the longest ESE reported, exceeding the 1.5 yr long event in the direction of the extragalactic source 2352+495 reported by Fiedler et al. (1994).

We searched for pulse broadening of J1643−1224 during the ESE by comparing pulse profiles measured during the ESE to the integrated pulse profile of the first 4 months of observations. Broadening is undetected within the relative uncertainty of 20%. The pulse width of J1643−1224 measured by our coherent dedisperser is 255 μs (Maitia 1998); consequently, the upper limit on the pulse broadening is $\tau_d \leq 50$ μs. Taylor & Cordes (1993) derives the expression $\tau_d \leq 1.1_{\rm ms} D_{\rm kpc} ({\rm SM})^{6/5} \nu_{\rm GHz}^{-22/5}$, with the distance D to the lens and the scattering measure SM. So the corresponding upper limit on the added scattering ${\rm SM_{lens}}$ during the ESE is 0.1 kpc $m^{-20/3}$ in the direction of J1643−1224. This upper limit does not provide a significant constraint on the turbulence of the local ISM in this direction, as it is more than 2 orders of magnitude larger than the standard value. In another direction, Lazio et al. (2000) found an added scattering ${\rm SM_{lens}}$ of $10^{-2.5}$ kpc $m^{-20/3}$ to account for the angular broadening of the source PKS 1741−038 measured by VLBI during an ESE.

Timing data of J1643−1224 have been acquired at Nançay along with the flux density series. However, the time baseline "off ESE" is not long enough to separate the signature of a possible added DM during the ESE from the signatures of the multiparameter fit (pulsar period, period derivative, astrometric and orbital parameters).

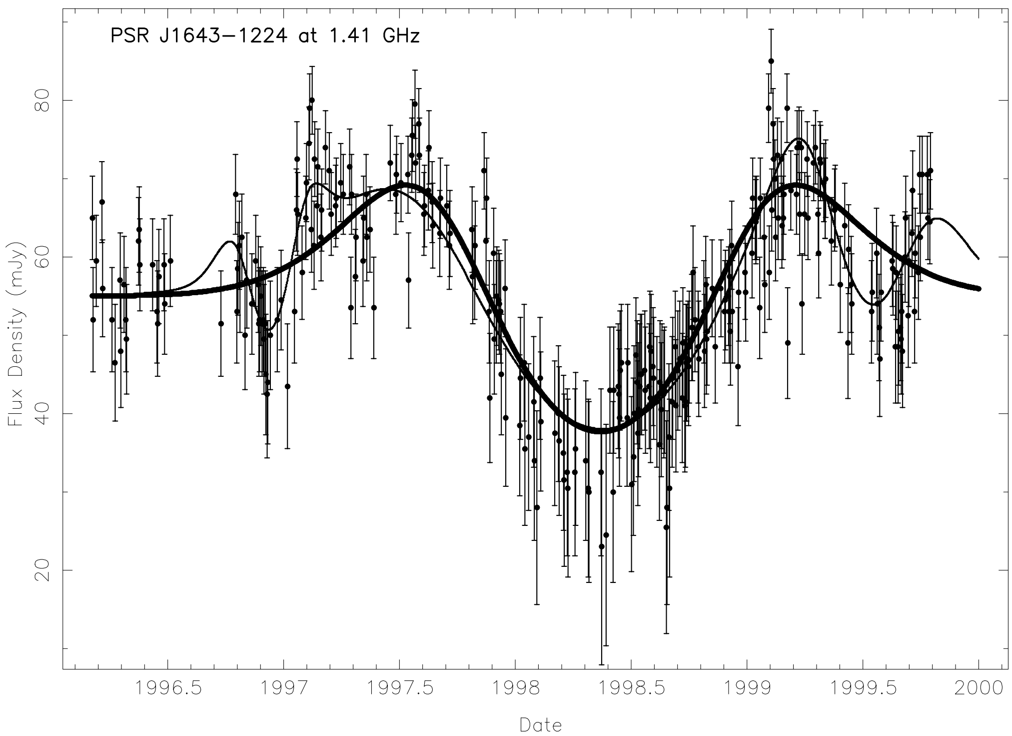

FIG. 1.—Radio light curve of the pulsar J1643−1224 measured at 1.41 GHz at Nançay showing a 3 year long ESE. This event is modeled as a refractive scintillation phenomenon by a fully ionized cloud (*thick line*, see fitted parameters in Table 1). The model with three clouds successively crossing the line of sight (*thin line*, fitted parameters in Table 2) is shown for comparison. In this radio light curve, the usual day-to-day scintillation caused by the turbulent ionized interstellar medium is apparent on top of the slow variation due to the ESE.

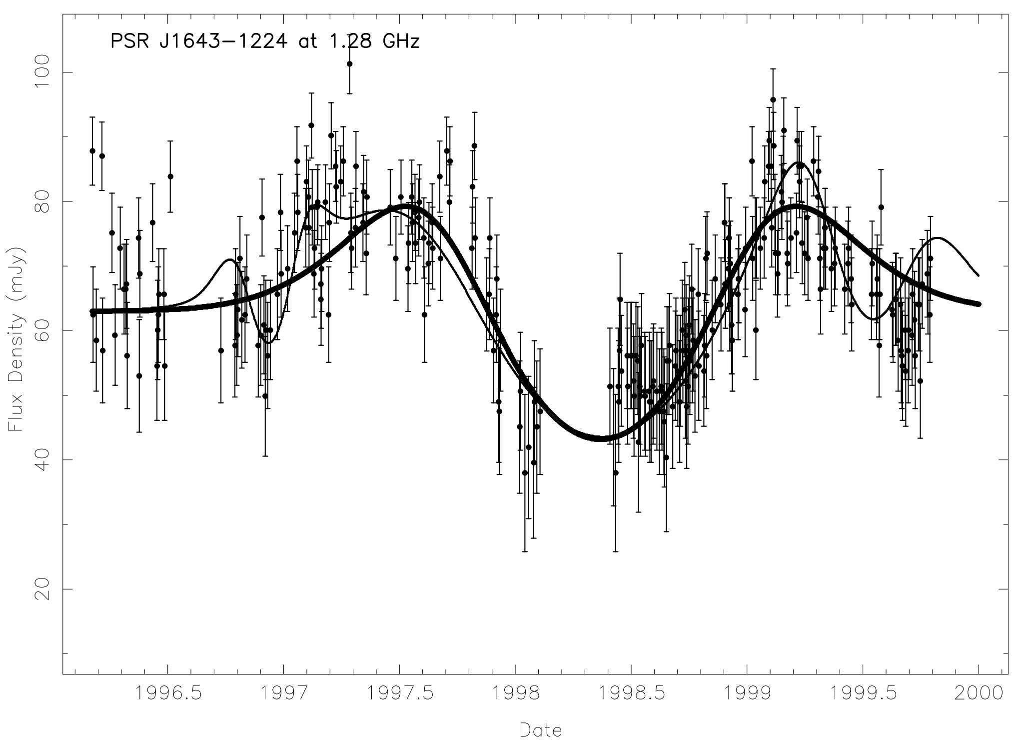

FIG. 2.—Radio light curve of the pulsar J1643−1224 measured at 1.28 GHz at Nançay showing the 3 year long ESE. No data were taken at 1.28 GHz between 1998 February and June because of technical constraints. This event is modeled as described in Fig. 1.

3. MODEL: REFRACTIVE DEFOCUSING IN THE DIRECTION OF THE PULSAR J1643−1224

In this section, the complex variation of the light curve of J1643−1224 observed at 1.28 and 1.41 GHz is modeled first with a single ionized cloud, and second with three clouds closely spaced together crossing, successively, the line of sight in an attempt to capture the variations at ingress and egress of the ESE.

3.1. *One-Cloud Model*

Interstellar scintillation has been treated in Cordes, Pidwerbetsky, & Lovelace (1986). They compute the flux density variation in the observer plane due to a phase screen perturbing the wave front at distance L. In this formulation, the flux density variation is expressed in terms of the gain G so that the intensity is $I = G \times I_0$ (I_0 = intensity without the screen). Their analytical formula (eq. [12] of Cordes et al. 1986) is

$$G = \left[1 + \frac{Lc}{2\pi\nu}\frac{d^2\phi(x)}{dx^2}\right]^{-1} , \qquad (1)$$

where c is the light velocity, ν is the observing frequency, and $\phi(x)$ is the phase of the incoming wave at abscissa x along the phase screen. The phase $\phi(x)$ depends on the integrated column density through the ionized interstellar medium and is, in radians,

$$\phi(x) = \lambda r_e N_e(x) , \qquad (2)$$

where λ, r_e, $N_e(x)$ are, respectively, the observing wavelength, the classical electron radius, and the column density through the screen at x. In our model, the cloud is assumed to be a slab with a Gaussian distribution for the electronic density along x. The cloud is defined by its transverse size $2a$ (Gaussian FWHM), peak electronic density n_0, and epoch of passage (t_0) at this peak (center of cloud). The thickness of the slab is chosen to be equal to the Gaussian FWHM $2a$, so that $N_e(x) = 2n_0 a \exp\{-[(x - x_0)/a]^2\}$, with the peak electronic density n_0 at x_0. The cloud crosses the line of sight with transverse velocity v_0 at distance L (screen), and so $x = v_0(t - t_0)$. By combining equations (1) and (2) above, the gain variation due to a single cloud expressed as a function of time t is

$$G = \left(1 + \frac{2L\lambda^2 r_e n_0}{\pi a} \times \exp\left\{-\left[\frac{v_0(t - t_0)}{a}\right]^2\right\} \times \left\{1 - 2\left[\frac{v_0(t - t_0)}{a}\right]^2\right\}\right)^{-1} . \qquad (3)$$

From equation (3), it is obvious that L and n_0 do not separate and v_0 and a are highly correlated. So, we have forced the cloud to be located at the mid-distance to the pulsar ($L = 2500$ pc) and fixed the transverse velocity v_0 at L to 95 km s^{-1}, using the proper motion of J1643−1224 measured by Toscano et al. (1999). This pulsar velocity is significantly larger than the Earth orbital velocity, which was ignored. The pre-ESE intensity I_0 was set to the mean flux density of 55 mJy computed over the first 4 months of the light curve at 1.41 GHz, when no systematic variation is apparent. We conducted an extensive grid search over the three-parameter space (n_0, a, t_0) and selected the final solution by minimizing the quadratic sum of the $O - C$ residuals over all observations at 1.41 GHz. The flux density uncertainties of the observations have not been used to weight the terms of this norm. We searched over [10, 300 e cm^{-3}] × [5, 80 AU] × [1998.0, 1998.8]. The final solution is in Table 1 and yields the postfit residual rms 6.8 mJy and mean −0.9 mJy (the intensity I_0 was not varied to make the residual mean exactly zero). The goodness of fit $\chi^2_N (= \sum(r_i/\sigma_i)^2/N)$ is 1.25. The parameters have been determined with the 1.41 GHz data only, but the resulting model is superposed both on the 1.28 and 1.41 GHz data in Figures 1 and 2. The postfit residuals are in Figure 3.

TABLE 1

FIT OF THE ONE-CLOUD MODEL TO THE FLUX DENSITY SERIES OF J1643−1224

Parameter	One-Cloud
n_0 (cm^{-3})	130
$2a$ (AU)	56
t_0	1998.370
χ^2_N	1.25

NOTES.—Measured at 1.41 GHz at Nançay. Final parameters found by a grid search over the three-parameter space (n_0, a, t_0) in minimizing the quadratic sum of the $O - C$ residuals. The nominal intensity I_0 was set to the pre-ESE value of 55 mJy, the distance and transverse velocity of the cloud were set to the pulsar mid-distance (2500 pc) and velocity 95 km s^{-1}. The postfit residual mean and rms are −0.9 and 6.8 mJy, respectively.

The pulsar J1643−122 is angularly close to the Upper Scorpius OB association at 160 pc. If the intervening cloud is associated with this region, then its electronic density is higher as shown by equation (3) when the distance L decreases. The electronic density n_0 can be derived straight-

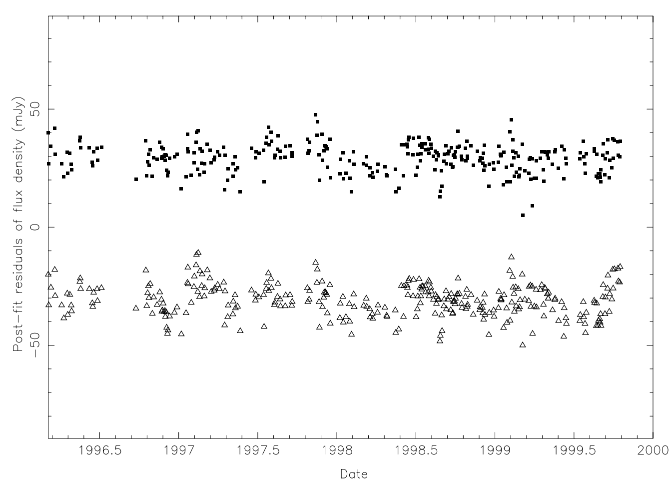

FIG. 3.—Residuals after fitting the one-cloud model (*open triangles*) and the three-cloud model (*filled squares*) to the flux density series of J1643−1224 measured at 1.41 GHz at Nançay. The series has been arbitrarily shifted by +30 and −30 mJy for clarity. The postfit residual means are actually −0.9 and −0.8 mJy and the rms are 6.8 and 6.2 mJy for the one-cloud and three-cloud model, respectively. The three-cloud model is only marginally better than the one-cloud model.

forwardly by scaling the value of n_0 in Table 1 with the ratio $(2500/160) \sim 16$.

A more elaborate model, in which the cloud is treated as a two-dimensional circular Gaussians (x, z) making the column density $N_e(x)$ of equation (2) an integral of z (line of sight), has been developed in Maitia (1998). The results are qualitatively the same as for the simpler model of this paper and are only different quantitatively, but the parameters are not drastically different.

3.2. *Three-Cloud Model*

In Figures 1 and 2, the observed light curves at ingress and egress do not resemble the simple "bumps" expected for the standard model of a single intervening cloud that focuses/defocuses the incoming rays (Clegg et al. 1998). In order to model more precisely the complex variations at ingress and egress, we distributed three Gaussian clouds along the screen axis (see sketch in Fig. 4). The expectation was that the two small clouds would be responsible for the variations at ingress and egress, and the large cloud in between would be responsible for the central depression of the light curve. The resulting gain $G_{\rm comb}$ of such a model is the combination of the three phase screens (clouds):

$$G_{\rm comb} = \left(1 + \frac{Lc}{2\pi\nu} \times \left[\frac{d^2\phi_1(x)}{dx^2} + \frac{d^2\phi_2(x)}{dx^2} + \frac{d^2\phi_3(x)}{dx^2}\right]\right)^{-1}, \quad (4)$$

where $\phi_1(x)$, $\phi_2(x)$, and $\phi_3(x)$ are the perturbations of the phase at x caused by the column densities $N_1(x)$, $N_2(x)$, and $N_3(x)$ of the three clouds. Similar to the previous model, each cloud is Gaussian and defined by its transverse size (FWHM $2a$), peak electronic density n_0, and epoch of passage at this peak (t_0). Equation (4) can be expressed as a function of time t and of these parameters as is explicitly done for the single-cloud model (eq. [3]). As previously, the distance (L) and transverse velocity (v_0) do not separate and were fixed for all clouds to the pulsar mid-distance 2500 pc and velocity 95 km $\rm s^{-1}$. This constraint forces the three clouds to be related. This is plausible, but this is an assumption in our work. The initial intensity was set to 55 mJy, as explained above. We conducted a grid search over the nine-parameter space $3 \times (n_0,\ a, t_0)$ and selected the final solution by minimizing the quadratic sum of the $O - C$ residuals over all observations at 1.41 GHz. Precisely, the search was carried over $[2,\ 100\ e\ {\rm cm^{-3}}] \times [2,\ 40\ {\rm AU}] \times [1996.8, 1997.2]$ and $[1999.3,\ 1999.7]$ for the two small clouds and over $[10,\ 300\ e\ {\rm cm^{-3}}] \times [5,\ 80\ {\rm AU}] \times [1998.0,\ 1998.8]$ for the large cloud, in fine steps. The final solution is presented in Table 2 and yields the minimum postfit residual rms 6.2 mJy, the mean -0.8 mJy, and the goodness of fit $\chi^2_N = 0.97$. The parameters have been determined with the 1.41 GHz data only, but the resulting model is superposed both on the 1.28 and 1.41 GHz data in Figures 1 and 2. The postfit residuals are in Figure 3.

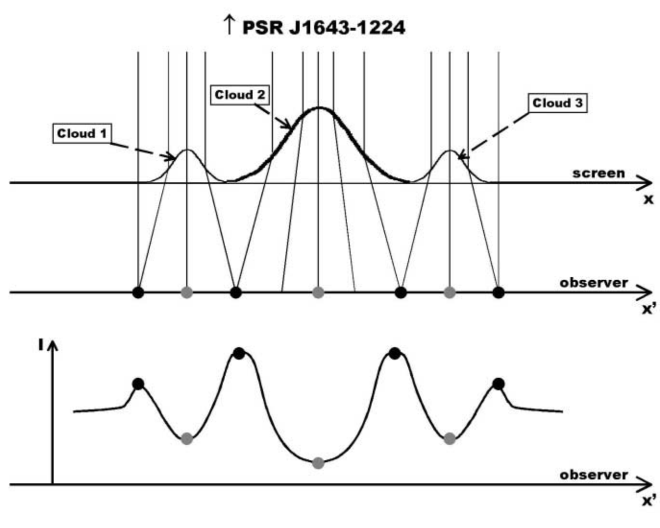

FIG. 4.—Sketch of the model based on refractive scintillation by three fully ionized clouds successively crossing the line of sight.

TABLE 2

FIT OF THE THREE-CLOUD MODEL TO THE FLUX DENSITY SERIES OF J1643−1224

Parameter	Cloud 1	Cloud 2	Cloud 3
$n_0\ ({\rm cm^{-3}})$	10	140	20
$2a$ (AU)........	10	51	18
t_0..................	1996.945	1998.378	1999.526
χ^2_N................	0.97	0.97	0.97

NOTES.—Measured at 1.41 GHz at Nançay. Final parameters of the three-cloud model found by a grid search over the nine-parameter space $3 \times (n_0,\ a, t_0)$ in minimizing the quadratic sum of the $O - C$ residuals. The nominal intensity I_0 was set to the pre-ESE value of 55 mJy, the distance and transverse velocity of the three clouds were set to the pulsar mid-distance (2500 pc) and velocity 95 km $\rm s^{-1}$. The postfit residual mean and rms are -0.8 and 6.2 mJy, respectively.

4. DISCUSSION

The fit of the three-cloud model for the ESE in the direction of J1643−1224 is only slightly better than the one-cloud model when comparing the postfit residuals. The three-cloud model removes some systematics in the postfit residuals, as apparent in Figure 3, but the rms of the postfit residuals is only improved by 10%. Although the complexity of the radio light curve of this event led to invoking several intervening clouds, the comparison of the two fits favors only slightly, not decisively, the three-cloud model. Also, since the probability of occurrence of an ESE in the direction of the millisecond pulsar B1937+21 is $P = 0.04$ (Lestrade et al. 1998), the probability of a three-cloud multiple event is $P \sim (0.04)^3$. This is much less probable than the occurrence of a single-cloud event. Finally, it is worth emphasizing again that two parameters (L and v_0) do not separate and were fixed to plausible a priori values in the fit. The present data set is not strong enough to decisively support the view that we have detected a multiple event, although it is possible.

The transverse dimension of the cloud in the one-cloud model is 56 AU and is significantly larger than the typical cloud of 1 AU found for 5 ESEs in the direction of the pulsar B1937+21 (e.g., Lestrade et al. 1998). The internal electron density of the cloud (130 $\rm cm^{-3}$) is 10^4 times larger than the mean interstellar electron density (0.03 $\rm cm^{-3}$). The corresponding pressure p/k is $10^6\ {\rm cm^{-3}}$ K and is extraordinarily high. Note that $p/k > 10^5\ {\rm cm^{-3}}$ K has also been found for the C I bearing interstellar gases in the work of Jenkins

& Tripp (2001). Unless these overpressurized clouds are confined by magnetic fields, they expand adiabatically into quasi-vacuum space and dissipate on the timescale of the sound crossing time ($2a/v_s$). The sound velocity v_s is 10 km s^{-1} for the temperature of ionization of hydrogen $T = 8000$ K (Spitzer 1968). The 56 AU cloud should dissipate in ∼29 yr. This lifetime is very short and implies a high rate of replenishment. The mechanism at work in the interstellar medium that yields such a high rate is unidentified and considered a difficulty. This makes plausible that the cloud is actually a filamentary structure with a large aspect ratio aligned with the line of sight and possibly confined by magnetic fields (Romani et al. 1987). No direct observational proof of such an elongated structure has been found though. Note finally that if the cloud is related to the OB association Upper Scorpius, the electron density n_0 is higher and the lifetime problem is exacerbated unless the ambient pressure near the OB association is higher and actually reduces the problem.

Alternatively, to alleviate this short lifetime problem, the theory of Walker & Wardle (1998) proposes that the ionized wind from a cold and self-gravitating cloud of molecular hydrogen whose surface is ionized by the UV radiation of the Galactic field could form a refractive shell responsible for ESEs at radio wavelengths. This would have profound implication for the matter content in the Galaxy owing to the large number of clouds implied by the observation. Most importantly, such a plasma lens would necessarily be axi- or mirror-symmetric and would produce a symmetric light curve unique to this theory (Walker 2001). There is some degree of symmetry apparent in our radio light curves of Figures 1 and 2, despite the lack of data at the final stage of the event after 1999 October when the telescope stopped. To test the degree of symmetry of our light curves, we have used the three-cloud model as a tool to force the two small clouds to be identical and symmetrically flanking the large cloud. We searched a large parameter space (six parameters) and found that the final solution yields a minimum postfit residual rms of 6.7 mJy and $\chi^2_N = 1.23$. The two small clouds have FWHM size 12 AU, density 5 e cm^{-3}, and $t_0 = 1996.915$ and 1999.715. The large cloud in this model has FWHM size 57 AU, density 130 e cm^{-3} and $t_0 = 1998.356$. The previous solution for the three clouds is marginally superior with a postfit rms of 6.2 mJy. This confirms quantitatively the impression that the symmetry in the light curve is only partial, contrary to expectation with the theory of Walker & Wardle (1998).

5. CONCLUSION

The ESE observed at 1.28 and 1.41 GHz in the direction of J1643−1224 is a remarkable event because of its duration of 3 years. The complex shape of the radio light curve recorded has been modeled with the standard refractive model of fully ionized clouds. The fit with a three-cloud model is slightly better (10% in postfit rms) than that obtained by using a single-cloud model. However, the comparison of the postfit residuals does not decisively favor the three-cloud model. Also, the probability of such a multiple event (three clouds successively crossing the line of sight) is very low, $P \sim (0.04)^3$, if based on the occurrence of ESEs in the direction of the B1937+21. In the final fit, the modeled cloud is as large as 56 AU, and its internal electronic density is ∼130 e cm^{-3}. This cloud is overpressurized and its lifetime is short (29 yr) implying a replenishment mechanism at work in the interstellar medium that is unidentified at present. This difficulty can be removed by invoking a filamentary cloud seen along its long axis to make its internal electronic density adequately small.

Alternatively, there is the proposition by Walker & Wardle (1998) that the ionized shell around a cold and self-gravitating cloud of molecular hydrogen could be the refractive structure. However, the theoretical light curve of such a model exhibits peaks at ingress and egress that are perfectly symmetric. The degree of symmetry in the observed radio light curves of J1643−1224, although noticeable, is not as high as this model requires. We conclude that the two models used (fully ionized cloud and H_2 cloud) do not satisfactorily represent all the features of our data in J1643−1224.

We thank J.-P. Drouhin, D. Aubry, B. Darchy, and N. Hallet for their help with the observations. We are grateful to M. A. Walker, G. Lagache, and an anonymous referee for constructive comments.

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