EXTREME SCATTERING EVENTS AND GALACTIC DARK MATTER

MARK WALKER AND MARK WARDLE

Special Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006, Australia

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ABSTRACT

"Extreme scattering events" (ESEs) are attributed to radio wave refraction by a cloud of free electrons crossing the line of sight. We present a new model in which these electrons form the photoionized "skin" of an underlying cool, self-gravitating cloud in the Galactic halo. In this way, we avoid the severe overpressure problem that afflicts other models. The UV flux in the Galactic halo naturally generates electron densities of the right order. We demonstrate, for the first time, a good reproduction of the prototypical ESE in the quasar 0954+658. The neutral clouds are a few astronomical units in radius and have masses \( \lesssim 10^{-3} M_\odot \). The observed rate of ESEs implies that a large fraction of the mass of the Galaxy is in this form.

Subject headings: Galaxy; halo — ISM: clouds — scattering

1. INTRODUCTION

Extreme scattering events (ESEs) were discovered 10 years ago during radio flux monitoring of a sample of compact radio quasars (Fiedler et al. 1987). The ESE phenomenon consists of dramatic flux changes occurring over several weeks to months. It is broadly agreed that ESEs are not intrinsic variations but, rather, apparent flux changes that are caused by refracting elements, a few astronomical units in radius, crossing the line of sight. Both random (Fiedler et al. 1987) and deterministic (Romani, Blandford, & Cordes 1987) lens structures have been proposed; in all cases, the refraction is attributed to free electrons. Two further points of consensus are that the blobs of free electrons must be Galactic and that they represent a distinct component of the interstellar medium (ISM) (Narayan 1988; see also Rickett 1990). This same component is thought to be responsible for episodes of multiple imaging of radio pulsars (Cordes & Wolszczan 1986; Rickett 1990)—a phenomenon that manifests itself as periodic fringes in the dynamic spectra.

Despite the attention that the ESE phenomenon has attracted (Romani et al. 1987; Romani 1988; Clegg, Chernoff, & Cordes 1988; Clegg, Fey, & Lazio 1998), the current state of understanding is unsatisfactory for two reasons. First, the implied pressure of the electron cloud—having an inferred density of photoionized material around a cool, self-gravitating cloud.

The pressure of the neutral material is balanced by the self-gravity of the cloud, while the ionized gas flows continuously from the surface; complete evaporation occurs over a timescale of order the Hubble time. We show in § 2 that this model reproduces the prototypical ESE light curves. The event rate for ESEs then leads to the robust conclusion (§ 3) that these clouds contribute substantially to the Galactic dark matter. In § 4, we note some key observational tests.

2. REFRACTION IN A PHOTOEVAPORATED WIND

The estimated cloud dimension and distance indicate that geometric optics are a good approximation. To proceed, we need to know the electron density distribution, from which we can calculate the bending angle of rays and hence the imaging properties of the cloud.

The photoionized material at the surface of the cloud is not bound but flows away as a feeble wind. Dyson (1968) constructed an analytic solution for the density profile of a spherically symmetric photoevaporated wind from a neutral cloud; his solution is plotted in Figure 1. The electron density at the surface of the cloud is given (in units of cm\(^{-3}\)) by 4.87 \times 10^8 (J_e/R)\(^{1/2}\), and in the local Galactic halo, at the solar circle, the ionizing photon field is \( J_e = 10^6 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) (Dove & Shull 1994). For a cloud radius \( R = 3 \times 10^{19} \text{ cm} \) (Fiedler et al. 1987), we obtain \( n_e(R) = 10^5 \text{ cm}^{-3} \). This model exhibits immediate strength in that the electron density required to explain the ESEs is a prediction of our model, whereas it is an assumption of existing models.

Dyson’s solution cannot be used directly for our calculations, however, since it is discontinuous at the ionization front, whereas we require the first and second derivatives of \( n_e \) to be well behaved. Physically, the thickness of the ionization front is just the absorption length of Lyman-limit radiation in the neutral medium. In turn, this is fixed by the temperature of the neutral atmosphere, via the requirement for pressure balance across the transition region. Another difficulty with Dyson’s solution is that \( n_e \) is determined implicitly, which is computationally inconvenient. We therefore employ the approximation \( n_e(x) \propto F(x)x^{-2}(1 + 4 \ln x)^{-1/2} \), where \( x = r/R \) is the radius expressed in units of the cloud radius and \( F \) is the Fermi function, taken to have a width of \( \delta x = 0.01 \) (corresponding to a temperature of 40 K in the neutral atmosphere). This distribution is plotted in Figure 1.
Making use of this electron density distribution, together with the phase-screen approximation, it is straightforward to compute light curves for a neutral cloud traversing the line of sight to a distant radio source. Figure 2 shows one such computation, appropriate to a cloud at a distance of 2 kpc and an impact parameter of $R/2$, along with the data for 0954+658. To simulate the nonzero size of the real source, the theoretical curves are smoothed by convolution with Gaussian functions. The adopted source model corresponds to 50% of the source flux being contained within a compact (lensed) component, with this component having a brightness temperature of $8 \times 10^{10}$ K.

The main qualitative features of these light curves are accounted for as follows. The phase velocity of the wave is increased by the presence of free electrons, so the cloud acts as a diverging lens. At low frequencies, the lens is powerful enough that almost all rays are refracted out of the line of sight, and only a small flux is measured when the lens is aligned with the source; this behavior is generic to all blobs of free electrons regardless of the details of their density distribution. Consequently, this regime of a very strong lens is not particularly helpful in distinguishing our model from other possible electron density distributions. At higher frequencies, however, the refractive index of the lens is much smaller, and typically rays are no longer refracted through sufficiently large angles that caustics form. Exceptions occur for rays that pass near the edge of the cloud: here the photoionized skin creates a large phase curvature in the wave front and can introduce caustics even at high frequencies. These caustics are evident as sharp peaks in the model light curve, and we note that similar features appear in the data; in our model, they are intimately associated with the presence of a peak in the electron column density at the limb of the cloud. The good qualitative agreement between our model and the data suggests that surface photoevaporation—which, of course, implies underlying cool material—is an essential feature of real ESE clouds. By contrast, the Gaussian electron density profile originally proposed (Romani et al. 1987) for ESEs cannot, even qualitatively, match the dual-frequency light curve of 0954+658.

3. IMPLICATIONS FOR DARK MATTER

Going beyond the interpretation of individual events, the principal implication of the new model is that there is much more mass present in the ESE clouds than had been previously thought (cf. Fiedler et al. 1987; but see also Pfenniger & Combes 1994). We now derive a lower limit on the total contribution of the ESE clouds to the mass of the Galaxy.

The sky-covering fraction, $f$, of the clouds is estimated from the flux-monitoring data (Fiedler et al. 1994) to be $f \sim 5 \times 10^{-3}$. We can immediately relate $f$ to the total surface density, $\Sigma$, in clouds at the solar circle: $\Sigma \sim 2 \langle \sin |b| \rangle f M/\pi R^2$, for cloud mass $M$ and radius $R$ (ESEs do not preferentially occur at low Galactic latitude, $b$, so we have set $\langle \sin |b| \rangle \sim 0.5$). These quantities are in turn related by the requirement of hydrostatic equilibrium within each cloud—$k T \sim G M_m/R$ at temperature $T$—leading to $\Sigma \sim f T/\pi G M_m R$. The cloud radius can be inferred from the event duration, in combination with an assumed transverse speed; a limit follows from setting the transverse speed equal to the escape speed for the Galaxy (500 km s$^{-1}$), giving $R \lesssim 3 \times 10^{14}$ cm. We expect that the cloud temperatures are at least as large as that of the cosmic microwave background (i.e., $T \approx 2.7$ K).
This lower limit is already larger than the total surface density of observable matter and is consistent with the value \((210 \, M_\odot \, pc^{-2})\) necessary to explain the Galactic rotation curve (Binney & Tremaine 1987). Taking the dynamically determined surface density as an upper limit on the contribution from ESE clouds, we estimate the individual cloud masses to be \(\lesssim 10^{-3} \, M_\odot\), highly substellar. Hence, the ESE data lead us to the conclusion that low-mass gas clouds make up a good fraction of the mass of the Galaxy.

We are currently reassessing the sky-covering fraction, \(f\) (Walker 1998), based on our theoretical model and the data of Fiedler et al. (1994). It is possible that \(f\) is as small as a few times \(10^{-4}\), in which case the lower limit on \(\Sigma\) would be an order of magnitude smaller. Even at this level, however, the cool, low-mass cloud population implied by the model remains a substantial and poorly understood component of the Galaxy. Moreover, because our estimate is a lower limit on the surface density, a smaller covering fraction still admits the possibility that such clouds do indeed dominate the dynamics of the Galaxy.

4. DISCUSSION

The result we have presented might appear surprising: can dark matter really be in this form and yet have escaped detection? It has been noted previously (e.g., Pfenniger, Combes, & Martinet 1994 and Gerhard & Silk 1996) that cool, dense gas clouds are not easy to detect directly and may indeed be a viable dark matter candidate. We reconsider these issues elsewhere (Wardle & Walker 1998), but some brief comments are appropriate here.

By virtue of their high density (\(\sim 10^{22} \, cm^{-3}\)) and low temperature, three-body reactions are sufficient to ensure that the clouds are molecular. The constituent material must have a very low dust/gas ratio in comparison with the diffuse ISM, otherwise the population would already have been revealed by optical extinction events of extragalactic stars (notably in the data generated by the microlensing searches; Paczyński 1996). A low dust content might reflect either a very low metal abundance or, possibly (B. Paczyński 1998, private communication), the settling of the refractory elements into a small, rocky core. Unless the clouds are dynamically unimportant (i.e., \(\Sigma \ll 10^2 \, M_\odot \, pc^{-2}\)), the measured \(\gamma\)-ray background at high Galactic latitudes (Kniffen et al. 1996) constrains the vertical distribution of the clouds to be much more extensive than the cosmic-ray disk, implying that the clouds are a halo population. (In turn, this means that they are pre-Galactic objects.) The small covering fraction, \(f\), of the clouds implies that each can make \(1/f\) orbits of the Galaxy before colliding with another cloud, implying a lifetime of order the Hubble time. The large column density of the individual clouds (of order \(10^{23} \, cm^{-2}\)) means that interactions with the diffuse gas in the Galactic plane involve a negligible deceleration. The lifetime against UV photoevaporation is also of order the Hubble time.

While the cool-cloud model we advance for ESEs is compatible with a variety of existing data, some specific observations can be made that would provide strong tests of the picture. We offer three such tests; the first of these is most intimately connected with ESEs and is in some sense the easiest experiment to perform. Although the clouds are predominantly molecular, a crude assessment of the relevant chemistry suggests that they should contain sufficient atomic hydrogen to make them opaque in the 21 cm line. Thus, while an ESE is in progress, there should also be a narrow absorption line present, in addition to the normal absorption spectrum of the source. (In our model, a similar connection should also hold between the 21 cm absorption and the multiple imaging of pulsars.) Small-scale (tens of AU) structure has already been reported in 21 cm absorption lines (Davis, Diamond, & Goss 1996; Frail et al. 1994), but the possible connection with ESEs has not yet been explored. The line velocities should reflect the kinematics of the cloud population, which are expected to be quite different from that of the diffuse H I in the Galactic disk. We note that, because of the multiple imaging that takes place, the absorption lines may appear saturated, but with a nonzero flux minimum.

Second, because the inferred column density of neutral material is so large, it is expected that the clouds are opaque to Rayleigh scattering (cf. Combes & Pfenniger 1997) between \(\lambda = 2000 \, \AA\) and the Lyman/Werner bands of H\(_2\), and opaque to Thomson scattering at X-ray energies. Thus, one in 1/\(f\) extragalactic UV/X-ray sources (of submilliarcsecond size) should appear extinguished at any one time, with events lasting a month or so.

Finally, we note that the recombination lines (H\(_\alpha\), etc.) from the cloud surface may be detectable if there is a sufficiently strong local source of ionizing radiation (Gerhard & Silk 1996). That is, clouds that are within a parsec of a hot star will be luminous sources of H\(_\alpha\) and may thus be rendered visible. It might also be possible to detect, from their H\(_\alpha\) emission, the clouds that are closest to the Sun. Many clouds are expected within a parsec, and these may appear as compact H\(_\alpha\) nebulae of large radial velocity and very high proper motion.

5. CONCLUSIONS

We have presented a new model for the cause of extreme scattering events, where radio wave refraction by ionized material magnifies ("lenses") a distant radio source. In our model, the ionized material is generated by the photoevaporation of an underlying neutral, self-gravitating cloud, so there is no difficulty in understanding the requisite high electron pressures; indeed, the ambient UV field in the Galactic halo naturally generates the necessary electron density. Moreover, we find it straightforward to reproduce the dual-frequency light curve of the prototypical ESE in the source 0954+658. These facts argue strongly for the soundness of the model.

It follows immediately that a large fraction of the mass of the Galaxy is in the form of cool gas clouds of up to Jovian mass, and only a few AU in radius. We are unable to falsify this picture with existing data, but with new observations some straightforward tests can be made.

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