

CHAPTER FOUR

Extreme Scattering Events, Distribution of Material
and IPS

INTERPRETATION OF EXTREME SCATTERING EVENTS

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Abstract. Extreme Scattering Events are sometimes manifest in the light-curves of compact radio-quasars at frequencies of a few GHz. These events are not understood. The model which appears to offer the best explanation requires a new population of AU-sized, neutral gas clouds; these clouds would then make up a large fraction of the Galaxy's dark matter. Independent of the question of which theoretical model is correct, if we extrapolate the observed behaviour to low radio-frequencies, we expect that the sky should be criss-crossed by a network of narrow caustics, at frequencies below about 700 MHz. Consequently at these frequencies sources should typically manifest additional, faint images which are substantially delayed with respect to the primary image. Although some examples of this type of behaviour are already known, it is expected that these are just the tip of the iceberg, with strong selection biases having been imposed by the instrumentation employed to date.

1. Introduction

Extreme Scattering Events (ESEs), Fiedler *et al.* (1987: F87), were discovered more than a decade ago but are still not understood. It is generally agreed that these events are due to refraction by intervening, ionised, Galactic gas (e.g. F87; Romani, Blandford and Cordes, 1987: RBC87), but there is no agreement on the astrophysical context in which this gas arises. Most models attempt to explain ESEs with the minimum possible extrapolation from conventional astrophysical pictures (see, especially, Deshpande and Radhakrishnan, 2000); this is the most conservative approach, and it seems very likely that at least one of these conventional models will prove relevant. There are, however, real difficulties in trying to explain some of the observed events – in particular the ESE in Q0954+658 – with conventional astrophysics, and this has motivated one rather exotic model in which a new population of dense, neutral gas clouds is invoked (Walker and Wardle, 1998).

The current lack of consensus on the correct physical picture for ESEs persists principally because the existing data have a fairly low information content. At this point the field is badly in need of some new observational initiatives; some ideas are presented in Section 6 (see also Walker, 2000).



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2. Basic Constraints on Lenses

The refracting structures which give rise to ESEs are conveniently referred to as 'lenses', although we should bear in mind that they might not be well-defined physical entities (model (iii) of Section 5). There are three basic properties of the individual lenses which are dictated fairly directly by the data on ESEs: (i) their transverse dimensions should be a few AU, (ii) the peak electron column-density should be of order 10^{17} cm⁻², and (iii) they should be symmetric. Point (i) follows immediately from the observed event durations (months) together with an assumed transverse speed of order 10^2 km s⁻¹. Point (ii) is deduced by requiring a strong lens which can magnify a large fraction of a source which is of order a milli-arcsecond in size. These points were recognised at the time of discovery of the ESEs (F87). One detail deserves clarification however: an upper limit on the distance of the lenses follows from their transverse dimensions in combination with the requirement that they be larger in angular size than the source. This reasoning is correct, but the angular size of the source has previously been taken as the scatter-broadened size, leading to a distance upper limit of order one kpc, and this is overly restrictive. For distances of a kpc or more, at high Galactic latitude, the lens is beyond the majority of the scattering material in the Galactic disk, and the relevant angular size is then the intrinsic source size; this can be substantially smaller than the scatter-broadened size, thereby relaxing the distance limit.

The third point has not previously been emphasised; it arises simply because the ESE light-curves are, crudely speaking, time-symmetric. At first sight this statement appears to have little value, because of the qualifying phrase 'crudely speaking', but this is not the case – most of the models which have been proposed for ESEs incorporate no lens symmetry whatsoever, and are therefore not good starting points for explaining even an approximate time-symmetry. That's not to say that such models are excluded, because it might be possible to construct versions in which the lenses do yield such behaviour, but the point remains that this property must be explained somehow. Some symmetry might be effected by the process of averaging over the source structure, but this is true only for the angular/temporal scales corresponding to the source size, below which flux variations are suppressed. One might argue that models which involve symmetric lenses should, in turn, explain why the observed time-symmetry is only approximate. This, of course, is trivial, because real astrophysical entities never conform exactly to the symmetries which are employed in modelling them.

Finally, if the approximate time-symmetry of the ESE light-curves is not accidental, it requires that any straight line drawn across the lens plane (representing the apparent path of the background source) should manifest a reflection symmetry about one point. In turn this indicates that the lens itself should have either mirror-symmetry and translational-invariance, or else it should be axisymmetric.

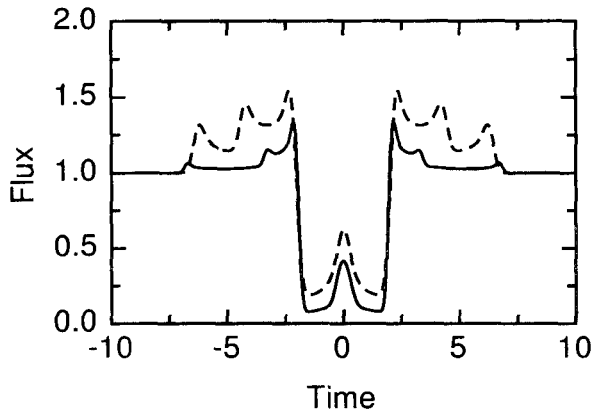


Figure 1. Low frequency light-curves for ESEs produced by mirror-symmetric (dashed) and axisymmetric (solid) lenses.

3. Further Constraints: The Case of Q0954+658

The ESE observed in Q0954+658 (F87) is by far the most spectacular event observed to date and deserves particular attention. This event exhibits a number of sharp peaks in the high-frequency (8.1 GHz) light-curve; these peaks are generally interpreted as being due to caustics. While there are four large peaks evident, there are roughly seven smaller, sharp peaks in this same light-curve, making eleven in total. Now caustic curves are closed curves, so that during a lensing event a source which crosses from the exterior to the interior of this boundary must later cross to the exterior again, giving rise to two peaks in the light curve. Furthermore, for a diverging lens the caustic curves come in pairs – one pair for every peak in electron column-density (provided the peak is sufficiently sharp). Thus, even if the source structure is a single-component only, the 8.1 GHz light-curve could be reproduced with as few as three column-density peaks, implying that the column density profile of the lens is likely to be very simple.

4. Nature of the Lens Symmetry

It is straightforward to decide which of the two possible lens symmetries (Section 2) is preferred; it is the axisymmetric lens. This can be seen immediately from Figure 1, which shows examples of the low-frequency light-curves arising from axisymmetric/mirror-symmetric lenses for which, in both cases, the source passes behind two peaks in electron column-density. (The mirror-symmetric lens consists of two parallel filaments, with Gaussian cross-sections, while the axisymmetric lens is a simple ring, again with a Gaussian cross-section.) A single Gaussian component is used for the source structure in these calculations. Caustic crossings are seen as the peaks in the light-curves; only seven are visible because the central

peak contains an unresolved pair in each case. Both light-curves exhibit the same deep flux depression, when the source is nearly on-axis. Conservation of energy demands that this power appears somewhere else in the observer's plane, and it is in this respect that the two lenses differ greatly: for the translationally-invariant lens the light-curve actually manifests this flux conservation, in the sense that the flux averaged over the whole event is equal to the unlensed flux, whereas this is not true for the axisymmetric lens. The data for Q0954+658 clearly favour the axisymmetric model.

5. Overview of Models

A number of models have been proposed to explain ESEs, in which the lenses are identified with a variety of physical phenomena. It should be borne in mind that the defining criteria for ESEs (F87, Fiedler *et al.*, 1994: F94) have been very loosely framed ('periods of unusual variability'), and this may have created heterogeneity in the class – more than one phenomenon could be represented amongst the events which have been dubbed ESEs. More than one lens model may therefore be relevant. A brief summary of lens models follows:

- (i) Random refracting elements (F87, F94)
- (ii) Magnetically confined filaments (RBC87)
- (iii) Steep spectrum turbulence (Deshpande and Radhakrishnan, 2000)
- (iv) Shock waves (RBC87; Clegg, Chernoff and Cordes, 1988)
- (v) Photo-ionised surfaces of giant clouds (Rickett, Lyne and Gupta, 1997)
- (vi) Photo-ionised winds from AU-sized clouds (Walker and Wardle, 1998).

Of these models, (i) is at present a purely phenomenological model whose physical viability cannot be readily assessed. Models (ii) and (iii) possess no particular symmetry, and are therefore disfavoured, while models (iv) and (v) involve strongly asymmetric lenses and are strongly disfavoured in this respect; only model (vi) generates the observed quasi-symmetry in a natural way. The necessary electron column densities and scale-sizes may in principle be realised by any of the models (ii–vi), but models (ii), (iv) and (v) need to be developed further before meaningful assessments can be made. Model (vi) appeared, initially, to yield the necessary column/scale-size combination in a very natural way, but McKee (2000) has since pointed out that a photo-evaporated wind would, in this context, have a modest ionisation fraction, so the calculation of the ionised column-density needs to be revisited for this model.

Notwithstanding a huge reduction in the predicted column of ionised gas, model (vi) currently appears to offer the best explanation for some of the ESEs – notably Q0954+658 – and the main issue is whether or not a population of dense, neutral clouds actually exists. Indeed this is a question with ramifications throughout astrophysics, because the neutral clouds would have to constitute a major component of the Galactic dark matter. The putative clouds cannot be excluded on the basis

of any existing data (Walker and Wardle, 1999), and this model provides a strong motivation for intensive study of the ESE phenomenon.

6. Future Work

How can we make progress in this field? A key aspect of the problem is the fact that ESEs are rare. This difficulty can most easily be addressed by working at low frequencies, where the refraction angles are larger and the cross-section for multiple imaging is increased. Indeed, for a lens which is localised in both transverse dimensions, the optical depth for multiple-imaging should scale as λ^4 , independent of the actual lens model. Taking the optical depth for Extreme Scattering (extragalactic sources) to be of order 5×10^{-3} at 2.7 GHz (F94), it is straightforward to predict that at frequencies below about 700 MHz there will be multiple images present most of the time. At these frequencies, then, the sky should exhibit a network of caustics. This does *not* mean that large flux changes will be happening continuously below this frequency, because the caustics are very narrow and in total cover only a tiny fraction of the sky; rather it means that there should typically be some extra *faint* images present. This phenomenon is, in fact, well known from pulsar studies (Cordes and Wolszczan, 1986; Rickett, 1990), where it manifests itself as interference fringes in the dynamic spectra; it is also very common, occurring for more than 10% of the time for some pulsars (J.M. Cordes, 2000, personal communication). However, while the connection to ESEs has long been recognised (e.g. RBC87), the exact relationship between the two effects remains to be understood. Regrettably, the multiple imaging phenomenon has not yet been exploited in any systematic way to learn about the lenses.

There are a number of possible avenues to improving the current situation by working with these multiple images. For example: one could gain some information on the structure of the lens simply by counting the number of images present; lens symmetry could be studied via VLBI observations through the course of a multiple imaging event; for long-duration events the evolution of the image delays could yield a ‘parallax’ measurement; and magnetic fields in the lenses could be studied by comparing the fringe patterns in different polarisations.

It is important to note that the faint, ‘extra’ images can be substantially delayed with respect to the main image, and the magnitude of the delay is roughly proportional to the geometric area covered by the images, hence proportional to the optical depth. Now refraction through an angle of order a milli-arcsecond should, over a distance of order one kpc, introduce a geometric delay of order 10^{-6} sec. Thus for lenses of order a milli-arcsecond in size, a strong lensing event (ESE) should introduce image delays of this magnitude, while multiple imaging at frequencies below 700 MHz will introduce delays hundreds of times larger. Such images would be extremely difficult to detect with conventional techniques, because the interference fringes would be so fine that they could not be resolved with existing spectrometers.

It is therefore to be expected that observations of multiple imaging phenomena have, to date, been subject to strong instrumental biases which allow us to see only images with relatively small delays, with the typical secondary images being censored. This bias increases in severity very rapidly as the observing frequency is decreased, with the maximum delay scaling roughly as λ^4 in this regime. To be confident that we are not introducing a bias, the only way forward appears to be the use of base-band recording, from which the temporal auto-correlation of the electric field, for example, can be computed out to large lags.

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