Magnetic lensing of ultra high energy cosmic rays [1]

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Abstract. We discuss several effects due to lensing of ultra high energy cosmic rays by the regular component of the galactic magnetic field. Large flux magnification around caustics can be a significant source of clustering in the arrival directions of UHECRs of comparable energy. We also discuss lensing effects in a hypothetical galactic magnetic wind model recently proposed to explain the extremely high energy cosmic rays so far observed as originating from a single source (M87). This model implies large flux magnifications, which reduce the power requirements on the source, and a significant asymmetry in the expected flux between the north and south galactic hemispheres.

LENSING IN THE REGULAR GALACTIC FIELD

Galactic and intergalactic magnetic fields play a major role in the physics of ultra high energy cosmic rays (CRs) [1]. The magnetic field of our Galaxy can lead to sizeable deflections of CR trajectories [2,3]. Here we emphasize the action of the galactic magnetic field as a giant lens which can sizeably amplify the CR flux arriving from any given source in some energy range [4,5]. We illustrate these effects within a bisymmetric spiral model for the regular component of the galactic magnetic field, with a value at the location of the solar system of 2 μG (see [4,5] for details). Precise predictions depend upon the detailed structure of the galactic magnetic field, which is not so well known. The main features should however be rather generic to any realistic model. In the case here considered magnetic lensing is relevant in the energy range 5×10^{18} eV $\lesssim E/Z \lesssim 5\times10^{19}$ eV, where Z is the CR electric charge. At higher values of E/Z deflections and magnifications are not very large, while at smaller energies the drift and diffusive regimes dominate.

A bundle of CR trajectories from an extragalactic source can be focused as it traverses the inhomogeneous galactic magnetic field. Its amplification is given by

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the ratio of the flux of particles reaching the Earth to that outside the region of influence of the galactic magnetic field. Fig. 1 illustrates the effect in the case of CRs that arrive from the direction to M87 in the Virgo cluster, specified by galactic coordinates $(\ell, b) = (282.5°, 74.4°)$. The flux from the principal image (the one visible at the highest energies) is amplified a few times at energies 10 EeV $\lesssim E/Z \lesssim 30$ EeV (1 EeV=10^{18} eV). At an energy $E/Z \approx 20$ EeV the source position lies along a caustic of the magnetic lens mapping. A pair of new images of the same source becomes visible from Earth at energies below the energy of the caustic.

The energy dependence of the amplification of each secondary image near the caustic is fitted with very high accuracy as $\mu_i(E) \approx \frac{A}{\sqrt{1-E/E_0}} \pm B$, $(i = 1, 2)$ (in the particular case displayed in Fig. 1, $A \approx 1.3$). This dependence can be intuitively understood as a consequence of the energy-dependence of the location of the caustics [5]. The number of events expected within a given energy bin is obtained from the convolution of the original spectrum produced by the source and the magnification due to the intervening magnetic field. In view of the energy dependence of the magnification near the caustic it is clear that in spite of its divergent behaviour, a finite number of events results. Taking as an illustration an injected differential spectrum that scales as $E^{-2.7}$, the integrated flux from two secondary images in the energy interval between 0.9 E_0 and E_0 turns out to be 12 A times larger than the flux of the principal image of the source in the same energy range in the absence of magnification. This is also $2.4A$ times the flux that would arrive from the principal image at all energies above E_0 if there were no magnetic lensing. Detection of an UHECR source in a narrow energy range around a caustic may thus be more likely than its detection at any higher energy.

The enhancement of the probability to detect events from a given source in a narrow energy range near the caustic implies a concentration of events around the

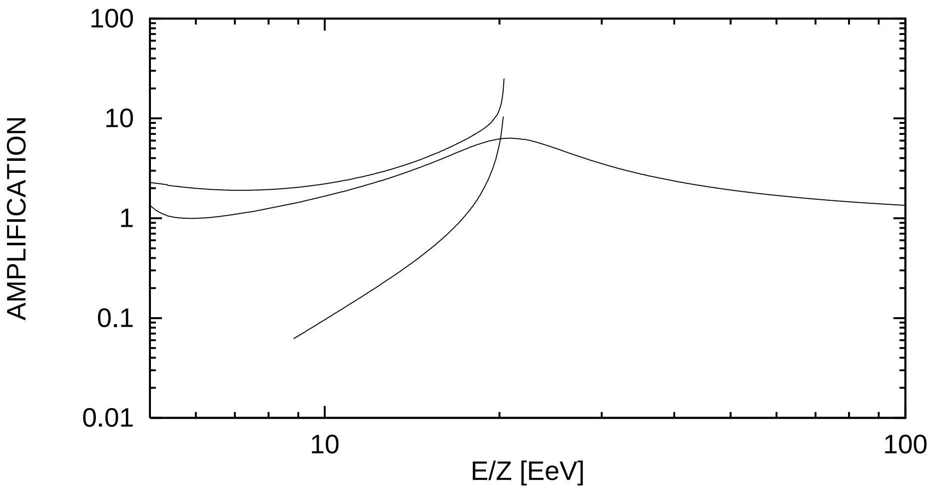

FIGURE 1. Amplification vs. energy of the flux in the principal and secondary images of an extragalactic source in the direction of M87.

location at which the new pair of images forms. Magnetic lensing around caustics is thus a potential source of clustering in the angular distribution of CR arrival directions, and should be taken into account in statistical analysis of small scale clustering of observed events. In this respect it is remarkable that the observed events in doublets and triplets are in most cases very close in energy [6]. This may be an indication that at least a fraction of the observed clustering of events may be due to magnetic lensing around caustics.

Caustics are not an uncommon feature, because they sweep a rather significant fraction of the sky as the ratio E/Z varies between around 50 EeV and a few EeV. To illustrate this point we display in Fig. 2 the contour plots of the magnification of the CR flux from point sources as a function of the CR arrival direction at Earth, for E/Z = 30 and 10 EeV. The critical curves in the amplification maps at the observer's plane correspond to the caustics in the source plane, and are within the black contours in Fig. 2.

We stress the fact that Fig. 2 plots the expected magnification for CRs arriving to Earth from isolated point sources. If the flux incoming to the region of influence of the galactic magnetic field were isotropic, the observed flux would also be seen isotropic, as a consequence of Liouville theorem. This fact was pointed out by Lemaître and Vallarta in their study of the deflection of low energy (few tenths of GeV) CRs by the Earth dipole magnetic field, in a paper which was quoted in a round table at this meeting as the first publication by a mexican author in the field of CRs [7].

Other implications of lensing by the galactic magnetic field include effects upon the observed CR composition. Nuclei with different charges are magnified by different amounts for a given energy, which may lead to a sizeable effect for sources whose magnification has a strong energy dependence (in particular around caustics) and which have a mixed composition.

Another peculiar feature of lensing in the vicinity of caustics is that the relative arrival time of events from a single image of a CR source does not necessarily increase with decreasing energy. It is often argued that the doublets in which the highest energy event arrived later than the other member in the pair can not arise

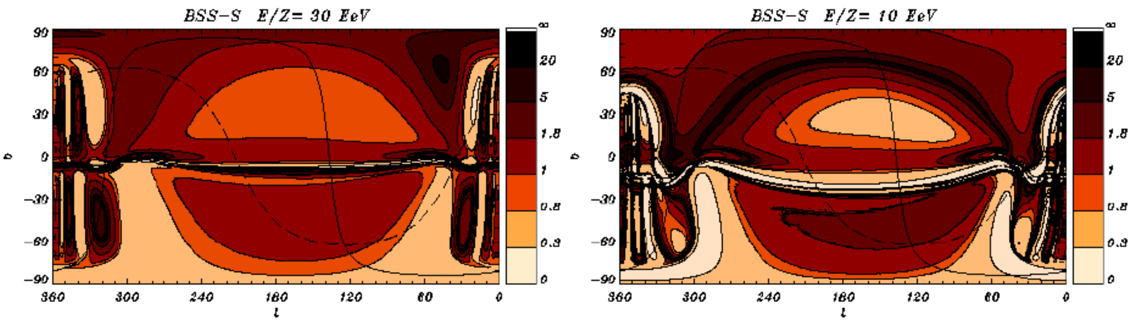

FIGURE 2. Contour plots of the magnification of the CR flux from a point source as a function of the arrival direction at Earth, for $E/Z = 30$ EeV (left) and 10 EeV (right).

from bursting sources. This is not necessarily true near a caustic.

LENSING IN A HYPOTHETICAL GALACTIC WIND

The angular distribution of the extreme high energy (EHE) events ($E \gtrsim 10^{20}$ eV) so far observed is consistent with isotropy. There are no known nearby sources close to their arrival directions considered to be a potential site for acceleration of cosmic rays to such enormous energies. It is possible that EHECRs are protons or nuclei emitted by a few nearby extragalactic sources, but then intervening magnetic fields should significantly bend their trajectories to explain why their arrival directions do not point to their place of origin. The regular component of the galactic magnetic field does not produce large deflections at these extremely high energies except over a heavy (large Z) component of the CR flux.

It has recently been speculated [8,9] that all the events so far detected at energies above 10^{20} eV may originate from M87 in the Virgo cluster, if the Galaxy has a rather strong and extended magnetic wind, if two out of the thirteen events considered are He nuclei (the rest being protons), and if intergalactic magnetic fields provide the extra deflection (of order 20°) needed to fine-tune the incoming particles in the appropriate direction (close to the direction to the northern galactic pole [10]) as they enter the wind.

Here we discuss some generic predictions due to flux magnification by magnetic lensing in this wind model that may serve to test its validity as more data becomes available [11]. The idealized magnetic wind model considered is an azimuthal field with strength given by $B = B_7\ 7\mu\mathrm{G}\frac{r_0}{r}\sin\theta\tanh(r/r_s)$ as a function of the radial spherical coordinate r and the angle to the north galactic pole θ. The distance from the Earth to the galactic center is $r_0 = 8.5$ kpc. B_7 is a normalization factor. Lensing effects depend upon the magnetic field strength and the CR energy and charge only through the combination $\overline{E} \equiv E/(ZB_7)$. The factor $\tanh(r/r_s)$ was introduced to smooth out the field at small radii. We took $r_s = 5$ kpc. We adopted a 1.5 Mpc cutoff for the extension of the field. The main lensing effects are produced

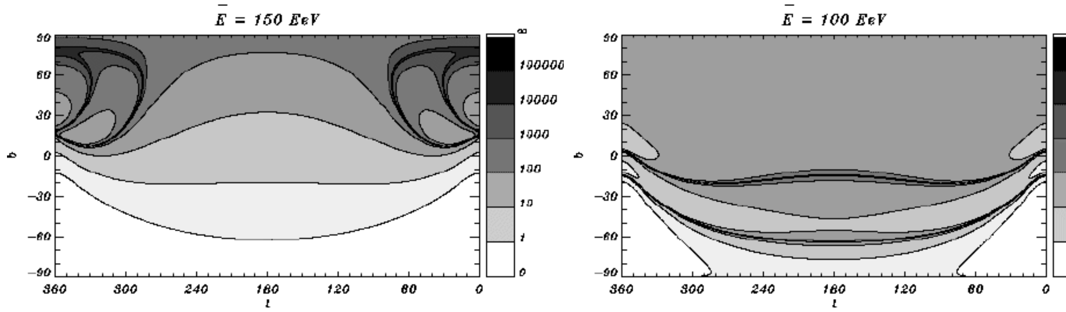

FIGURE 3. Contour plots of the magnification by the galactic magnetic wind of the CR flux from a point source as a function of the arrival direction to the Earth for two different values of $\overline{E} \equiv E/(ZB_7)$.

at distances larger than 10 kpc and less than a few hundred kpc, so that taking $r_s = 10$ kpc or a cutoff at 1 Mpc leaves the results essentially unchanged.

Fig. 3 shows contour plots of equal magnification for given CR arrival directions. Huge magnifications, in excess than a factor of 100, are attained in large regions of the sky. Most of the sky is swept from north to south by the critical lines (which are also indicative of multiple image formation) as $\overline{E}$ varies between 150 EeV and just below 100 EeV.

CRs at different energies enter the galactic wind from different directions if they have suffered magnetic deflections in their way. It is nevertheless instructive to consider fixed incoming directions, to illustrate some of the generic features of lensing by the galactic wind. Figure 4 displays, in its left panel, the energy-dependent magnification of the flux of CRs that enter the galactic magnetic wind from the direction $(\ell, b) = (270°, 88°)$, for the principal (P) as well as for the secondary images (A, B). The right panel of Fig. 4 shows the expected arrival directions of 50 equally probable events from a source that injects CRs from the same fixed direction with a differential energy spectrum proportional to $E^{-2.7}$.

The principal image is magnified by a factor of order 10 at $\overline{E} \approx 200$ EeV, is further amplified at intermediate energies, and then its magnification starts to rapidly decrease while $\overline{E}$ is still above 100 EeV. Its apparent position moves south as the energy decreases. Secondary images appear at the energy at which the caustic crosses the source position. One of the secondary images moves north and remains highly magnified, with an amplification factor above 100, while the other moves south and is quickly demagnified. Notice that there are no events at southern galactic latitudes below a certain energy threshold.

The fact that magnification factors well above 100 are attained in a significant energy range, with $\overline{E}$ below 150 EeV, reduces the energy requirements upon the source, that would need to be a factor of more than 100 less powerful than if unlensed to provide the same observed flux in this energy range.

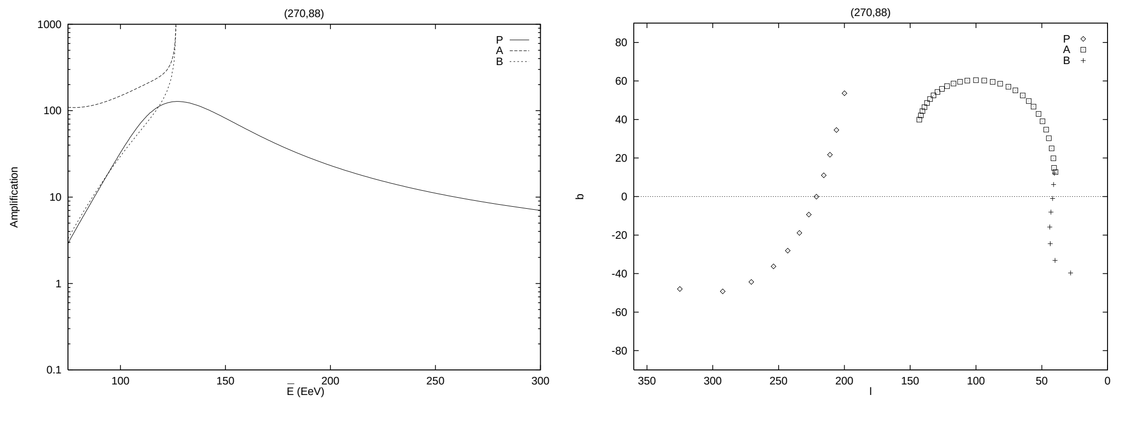

FIGURE 4. Amplification vs. energy of the CR flux that enters the galactic wind from $(\ell, b) = (270°, 88°)$ (left), and predicted arrival directions of 50 EHECR events with $\overline{E}$ above 75 EeV assuming an injection flux proportional to $E^{-2.7}$ (right).

A definite prediction of this model is a strong asymmetry between events arriving from the northern and southern galactic hemispheres. Although with the present EHE data, which involves only the northern terrestrial hemisphere and hence mainly the northern galactic one, it is not yet possible to test this asymmetry, the future operation of the Auger observatory, will allow to check the viability of this model. A latitude dependent upper cut-off value below 2×10^{20} eV for CR protons arriving to the south and lower fluxes in the south than in the north above 10^{20} eV are generic predictions of this scenario.

A galactic wind with a local value smaller than the 7 μG adopted in [8] could in any case have interesting observational consequences if EHECRs have a significant component which is not light. The flux of heavy nuclei could thus be strongly amplified by the galactic wind field, while the proton flux at the same energy would remain essentially unlensed. A transition to a heavy composition could thus result at extremely high energies.

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