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Magnetic lensing of Extremely High Energy Cosmic Rays in a Galactic wind

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Abstract: We show that in the model of Galactic magnetic wind recently proposed to explain the extremely high energy (EHE) cosmic rays so far observed as originating from a single source (M87 in the Virgo cluster), the magnetic field strongly magnifies the fluxes and produces multiple images of the source. The apparent position on Earth of the principal image moves, for decreasing energies, towards the galactic south. It is typically amplified by an order of magnitude at $E/Z \sim 2 \times 10^{20}$ eV, but becomes strongly demagnified below 10^{20} eV. At energies below $E/Z \sim 1.3 \times 10^{20}$ eV, all events in the northern galactic hemisphere are due to secondary images, which have huge amplifications ($> 10^2$). This model would imply strong asymmetries between the north and south galactic hemispheres, such as 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. The large resulting magnifications reduce the power requirements on the source, but the model needs a significant tunning between the direction to the source and the symmetry axis of the wind. If more modest magnetic field strengths were assumed, a scenario in which the observed EHE events are heavier nuclei whose flux is strongly lensed becomes also plausible and would predict that a transition from a light composition to a heavier one could take place at the highest energies.

Keywords: High-energy cosmic rays.

Contents

1. Introduction

The origin and nature of the highest energy cosmic rays so far detected stands as a puzzle for contemporary astrophysics [1]. The flux of protons with energy around and above 70 EeV (1 EeV = 10^{18} eV) should be significantly attenuated over distances of order 100 Mpc due to their interaction with the cosmic microwave background [2]. Nuclei should be attenuated over even shorter distances [3]. Nonetheless, fourteen events with estimated energy above 100 EeV have been detected so far, largely exceeding the expected fluxes if the sources are at cosmological distances. This suggests a "local" origin of extremely high energy cosmic rays (EHECRs). The puzzle arises because the angular distribution of the fourteen EHE events is consistent with isotropy (given the limited statistics and insufficient sky coverage) and there are no known sources near their arrival directions and inside our 100 Mpc neighborhood considered to be a potential site for acceleration of cosmic rays to such enormous energies.

A potential solution to the puzzle is that EHECRs are protons or nuclei that do indeed originate in sources within a 100 Mpc neighborhood of Earth, but their arrival directions do not point to their place of origin because their trajectories are significantly bent as they traverse intervening magnetic fields. The regular component of the magnetic field in the Milky Way leads to sizeable deflections [4, 5] and other magnetic lensing effects upon ultra high energy charged cosmic rays, such as flux (de)magnification and multiple image formation [6, 7]. This is the case, however, only if the ratio E/Z between energy and electric charge of the CRs is below approximately 30 EeV. The EHECRs would thus be severely affected by the regular component of the galactic magnetic field only if they have a significant component which is not light.

It has recently been speculated [8] 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. Indeed, such extreme galactic magnetic wind is compatible with an origin for all EHE events at less than 20° from the direction to the Virgo cluster, if two out of the thirteen events considered are He nuclei, the rest being protons. One event was excluded from the dataset due to the large uncertainties in its energy determination.

In this paper we further develop the analysis of the scenario put forward in [8]. The determination of the deflections of CR trajectories is insufficient to test the consistency of the scenario with the observational data and to determine its generic predictions, because magnetic lensing also produces huge flux (de)magnification and multiple image formation, effects that we analyse here and which turn out to be crucial to establish the detailed features of the model.

2. Flux enhancement by magnetic lensing in a galactic wind

We consider an azimuthal magnetic field with strength given by

$$B = B_0 \frac{r_0}{r} \sin\theta \tanh(r/r_s) \tag{2.1}$$

as a function of the radial (spherical) coordinate, r, and the angle to the north galactic pole, θ. The distance from Earth to the galactic center is $r_0 = 8.5$ kpc and the local value of this wind field is taken as $B_0 = 7\mu$G. This field has the $\sin\theta/r$ dependence adopted in ref. [8] with an extra smoothing in the Galactic center region, given by the $\tanh(r/r_s)$ factor, introduced to avoid unphysical divergences at small radii. For definiteness we took $r_s = 5$ kpc but the results are not dependent on the precise way in which this smoothing is performed. We also adopted a 1.5 Mpc cutoff for the extension of the field as in ref. [8].

The trajectories of CR protons in the Galactic wind magnetic field are obtained by backtracking antiprotons leaving the Earth. The azimuthal nature of this field bends all the trajectories towards the north galactic pole [8, 9]. The incident direction outside the region of influence of the wind points at less than 15° from the north pole for all the observed EHE events, except for the two most energetic ones. The two most energetic events could also come from that cone only if their electric charge is assumed to be larger, for example if they are He nuclei. This fact has been exploited to suggest that all the EHE events may have a common source, M87 in the Virgo cluster [8], which is indeed at $b = 74.4°$, i.e. not far from the north galactic pole. Clearly at this level one has to be satisfied with this kind of accuracy in the pointing since the wind model is highly idealised and one is also neglecting the additional deflections that should take place near the source and in the travel through the intergalactic medium. This will also require that our conclusions be based only on the general qualitative features of the model, rather than on its specific details.

It has been pointed out that large scale magnetic fields not only deflect CR trajectories but that they also act as a giant lens (de)magnifying the fluxes received from different directions and leading to multiple image formation [6]. For a given source this lensing effect varies with the energy and thus can enhance or attenuate the fluxes differently for different energies. This effect turns out to be quite strong in the Galactic wind model under consideration, so it has to be taken into account in a complete analysis of this scenario.

The magnification due to the lensing effect is computed as the ratio between the area subtended by a parallel bundle of particles arriving to the Galactic wind region and that subtended by the same particles at their arrival to the Earth [6]. Fig. 1 shows the contour plots of equal magnification for three values of the E/Z ratio. Each point denotes the arrival direction of a CR to the Earth in galactic coordinates (ℓ, b). We observe that huge magnifications, in excess than a factor of 100, are attained in large regions of the sky. This is the case for most directions with $b > 15°$ for $E/Z = 150$ EeV and with $b > -15°$ for $E/Z = 125$ EeV. The critical lines (lines where the magnification diverges and that correspond to the caustic lines in the source plane) move quickly to the south as the energy decreases. Most of the sky is swept by the critical lines as E/Z varies between 150 EeV and just below 100 EeV. Since the magnification is huge in the regions close to these lines, a strong enhancement in the detection probability of events with energies close to that at which the caustics cross the source direction is expected.

3. Multiple images

The presence of critical curves in the magnification maps indicates that the magnetic lensing effect of the Galactic wind produces multiple images of the source for some source directions in the range of energies considered. This fact is most clearly seen from the plots of the "sky sheets", representing the projection of a regular grid of observing directions at Earth to the directions outside of the Galactic wind region. This kind of plots map the arrival direction(s) at which a CR is observed at Earth to the direction from where the CR arrived to the region of influence of the magnetic field. Fig. 2 shows this sheet in polar coordinates centered in the north pole for three values of the E/Z ratio. The stretching of this sky sheet reflects the magnification for those source directions, very stretched regions being strongly demagnified and those where the sky sheet is densely contracted being very magnified. The fold lines correspond to the position of the caustics, where the magnification diverges. Sources located in regions where the sheet is folded are observed at Earth from several different directions. For $E/Z = 175$ EeV a couple of folds ending into two

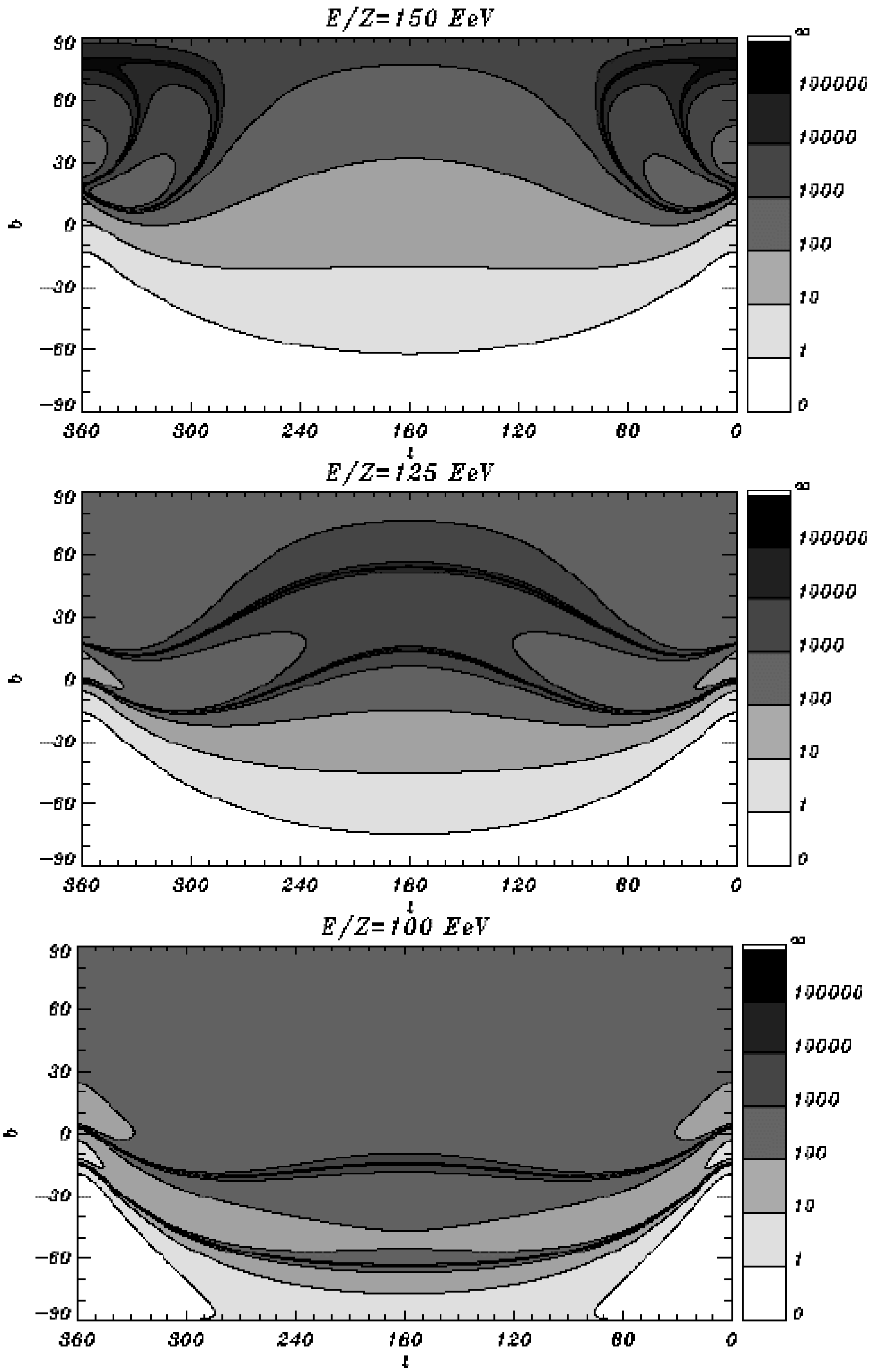

Figure 1: Contour plots of the magnification due to the galactic magnetic wind model of the CR flux from a point source. The plots are shown as a function of the arrival direction at the Earth and for three different CR energies.

cusps (a lip) develop. A source inside the folds has three different images. Note however that the folds cover only a tiny fraction of the sky and thus this is a rare

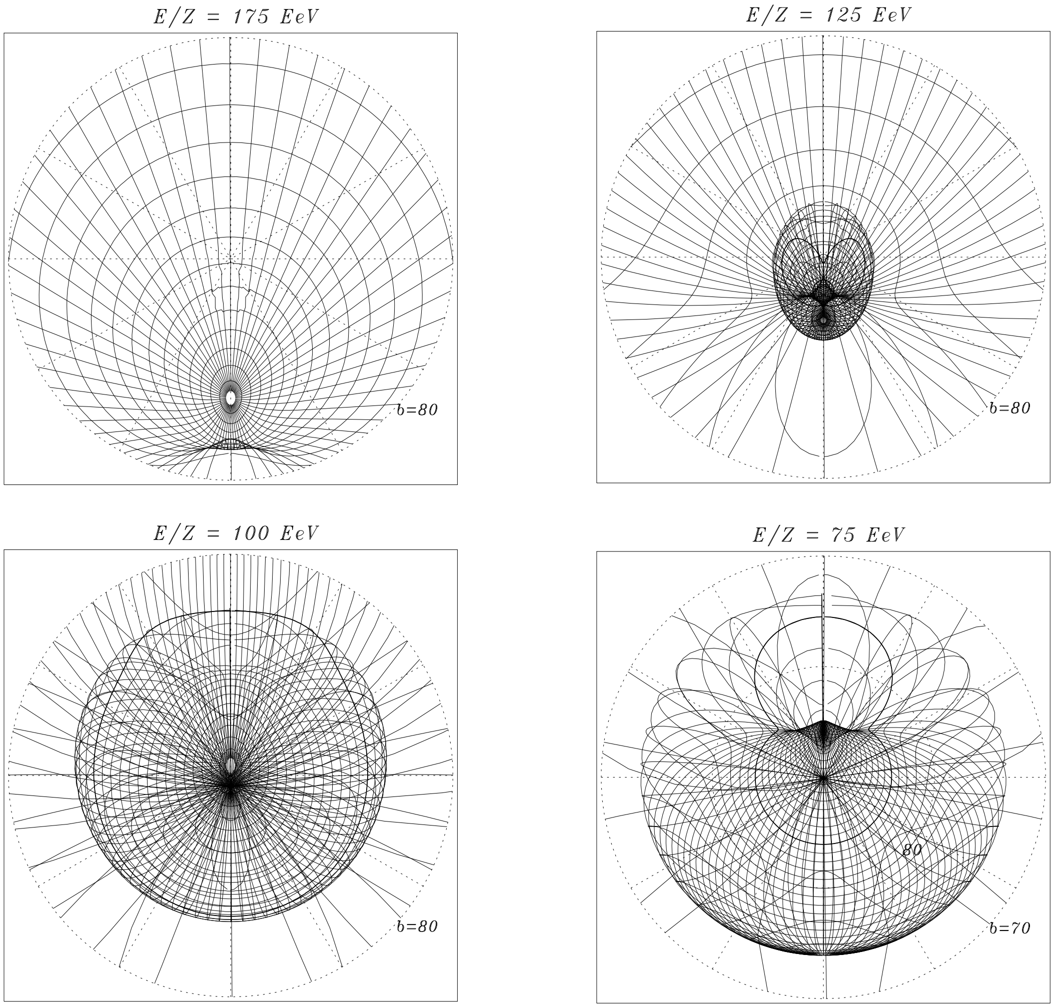

Figure 2: Projection of a regular grid (in polar coordinates centered at the northern galactic pole) of the sky seen on Earth onto the source sky, i.e. the corresponding directions from which CRs enter the galactic wind. Sources located in regions where this "sky sheet" is folded have multiple images. Three images are seen if the source is inside the "blob" (which subtends an angular diameter of the order of 5° at $E/Z = 125$ EeV, 15° at $E/Z = 100$ EeV, and 30° for $E/Z = 75$ EeV), five images if it is inside the much smaller "diamond". Dashed lines represent a polar grid of source directions, spaced every 10° in galactic latitude and 30° in longitude. In the lowest energy case the $b > 70°$ cap is plotted while in the rest just the $b > 80°$ cap is shown in order to better appreciate the details.

effect at these energies. For $E/Z = 125$ EeV a complete blob has developed on the sheet. The blob is connected to the rest of the surface through a diamond shaped caustic (this is due to the Earth eccentric position in the Galaxy: for observers in the symmetry axis, e.g. at the Galactic center, the diamond would shrink to a point[1]).

[1]These caustics are analogous to those associated to elliptical lenses, or spherical ones with

The southernmost critical line in the second panel of Fig. 1 corresponds to the diamond caustic in Fig. 2, while the northern critical line corresponds to the circular fold caustic. The huge amplifications found for all the directions in the northern sky above the southernmost critical line reflect the fact that a large fraction of the sky seen on Earth is shrinked inside the blob, and hence the sheet is highly contracted there. While the region inside the diamond caustic (leading to five images) is still tiny in the source sky, the blob (leading to three images) covers a region of $\sim 5°$ diameter. We have also drawn, with a bold solid line, the directions for which the cosmic rays would arrive to the Earth along the galactic equator. It is clear that all cosmic rays with $E/Z = 125$ EeV with arrival directions in the northern galactic hemisphere actually enter the galactic wind from directions less than $2.5°$ away from the center of the blob. At smaller energies a still larger fraction of observing directions are swallowed into the blob (this corresponds to the motion of the critical lines towards the south in Fig. 1), which at $E/Z = 100$ EeV has an angular diameter of the order of $15°$. At $E/Z = 75$ EeV the diamond has nearly disappeared, and a new blob starts developing on top of the previous blob. At this energy the angular diameter of the main blob, corresponding to the source positions leading to multiple images, is already larger than $30°$.

It is important to notice that only if the blob is on top of the source position (eventually displaced by the energy dependent deflections due to the extragalactic magnetic fields) the cosmic rays are able to reach the Earth along directions above the southernmost critical line in Fig. 1, which for $E/Z = 125$ EeV already covers the whole northern hemisphere. Hence, protons with $E < 125$ EeV can only reach the northern hemisphere as extremely magnified ($A > 10^2$) secondary images.

4. Generic predictions

We now discuss some generic features of the scenario in which all the CR events with energies above 10^{20} eV so far detected originate from M87 in the Virgo cluster, their trajectories having been significantly bent by this rather strong and extended galactic magnetic wind [8]. These generic properties may serve to test the validity of the scenario as the data on EHECRs increase.

Detailed predictions depend upon the exact nature and strength of the galactic wind, as well as upon the precise deflections suffered by the CR trajectories from the source in M87 up to their entrance to the galactic wind. Nevertheless, the generic features of any scenario compatible with current observations, mainly determined by the focusing properties of the magnetic wind, should be similar to those in the highly idealised model analysed here.

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external shear, in gravitational lensing [10], for which the central diamond shrinks to a point-like caustic in the circularly symmetric limit.

In the model under consideration, all thirteen EHECR events enter the galactic wind region along different directions, most of them just between 2° and 5° away from the direction to the north galactic pole, and at most separated by 12° from the vertical direction. Intergalactic magnetic fields are assumed to be responsible for these energy-dependent deviations from the direction to M87.

This scenario predicts a strong asymmetry between the north and south galactic hemispheres. Consider for instance that all EHECRs enter the galactic halo less than 15° away from the direction to the north galactic pole. The lines in Figure 3 display the southernmost possible arrival directions on Earth, for several values of E/Z.

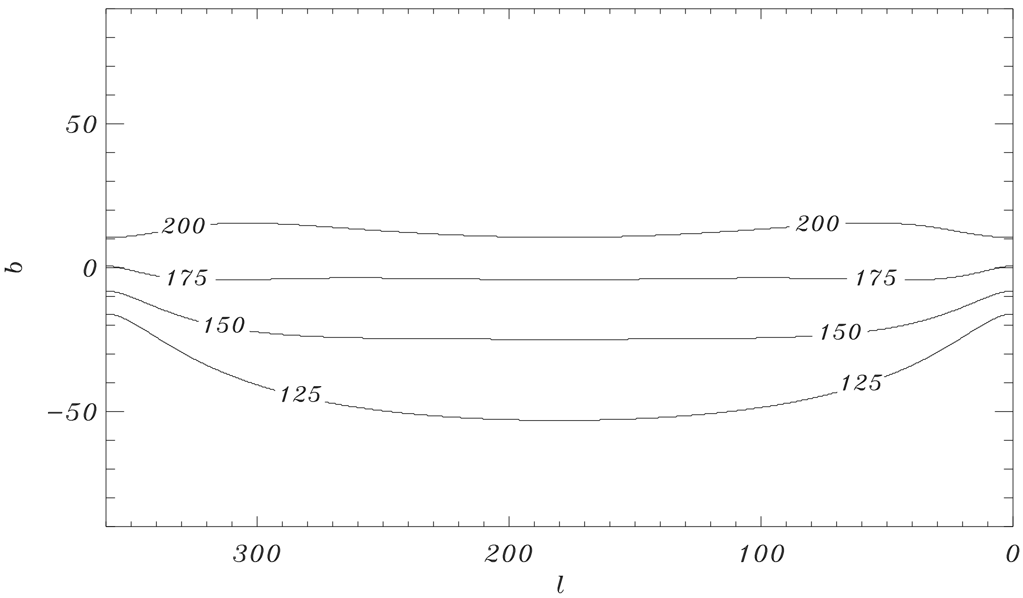

Figure 3: Cosmic rays that enter the galactic wind less than 15° away from the direction to the north galactic pole reach Earth from directions above the lines drawn, corresponding to different values of E/Z.

This scenario thus implies that no charged cosmic rays should arrive on Earth from directions below the lines drawn in Fig. 3 for values of E/Z larger than that indicated along each line. Certainly CRs may arrive below these lines if they enter the galactic wind with an inclination larger than 15° from its symmetry axis, but then they do so with smaller magnifications (or rather with large demagnifications) as larger is the inclination. Thus, even if there were other EHECR sources as powerful as M87 in our local (less than 100 Mpc) neighborhood, their flux will not be significantly magnified (or rather they will be significantly demagnified) if the CRs enter the galactic wind far away from the direction to the north galactic pole. Only if E/Z is above a few times 10^{21} eV does the observed flux approach its unlensed value, and the CRs arrival directions point to their true source location.

Even if there is a unique source, CRs at different energies should 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 further illustrate some of the generic features of lensing by the galactic wind already discussed in the previous sections. Figure 4 displays the energy-dependent magnification of the flux of CRs that enter the galactic magnetic wind from directions $(\ell, b) = (270°, 88°)$ and $(270°, 85°)$, for the principal (P) as well as for the secondary images (A, B). Figure 5 displays the change in the observed arrival directions of CRs with these entrance directions as the energy is lowered down to $E/Z = 75$ EeV.

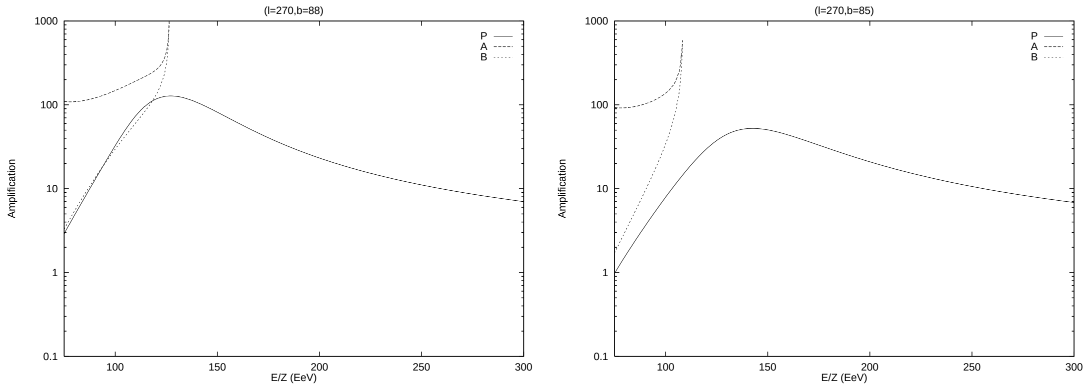

Figure 4: Energy-dependent amplification of the CR flux that enters the galactic wind from $(\ell, b) = (270°, 88°)$ (left) and $(\ell, b) = (270°, 85°)$ (right).

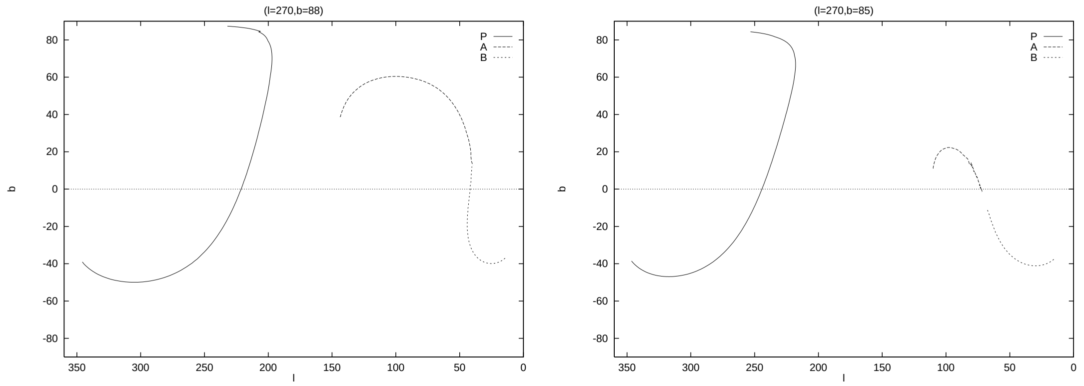

Figure 5: Arrival directions of CRs that enter the galactic wind from $(\ell, b) = (270°, 88°)$ (left) and $(\ell, b) = (270°, 85°)$ (right), as their energy falls down to $E/Z = 75$ EeV

The principal image is magnified by a factor of order 10 at $E/Z \approx 200$ EeV, is further amplified at intermediate energies, and then its magnification starts to rapidly decrease while E/Z 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, with formally divergent magnifications. 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. The secondary images appear and remain in the opposite east-west hemisphere than that in which the principal image is seen.

The general features displayed in these examples are generic to different entrance directions. However, the precise energy and location at which secondary images form, the energy at which the principal image is most magnified, and the exact amount of magnification attained depend sensibly on the entrance direction. For instance, if the entrance direction is more than about 8° away from the north galactic pole, then secondary images appear only below 100 EeV, and the principal image acquires smaller and smaller maximum magnification as the entrance direction is farther away from the vertical.

The expected energy and angular distribution of observed EHECRs can be exemplified considering again some fixed entrance directions and assuming that the differential flux injected by the source scales for instance as $E^{-2.7}$. We take the detecting system to have the same efficiency at all energies within the range considered, which we divide in 50 bins of equal detection probability. We consider values of E/Z larger than 100 EeV only. Figure 5 displays the arrival directions of the events that would be detected in each case.

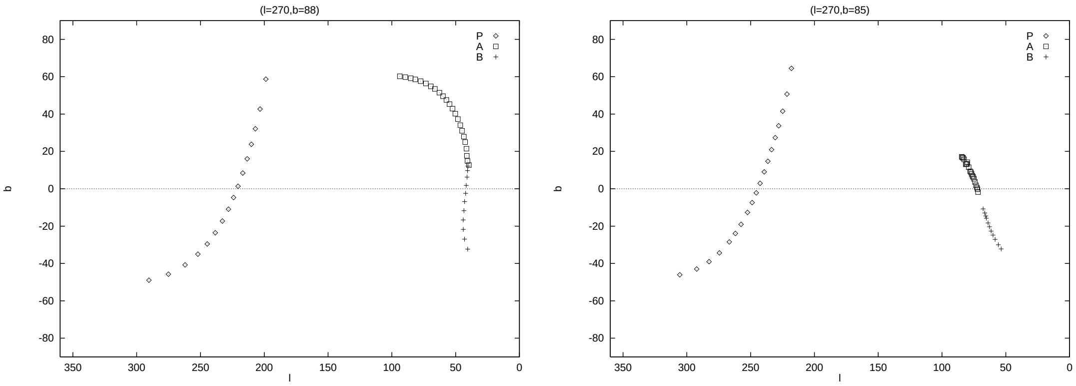

Figure 6: Predicted arrival directions of 50 EHECR events with E/Z above 100 EeV, if they enter the galactic wind from $(\ell, b) = (270°, 88°)$ (left) and $(\ell, b) = (270°, 85°)$ (right), assuming an injection flux proportional to $E^{-2.7}$.

As already discussed, we see that there are no events at southern galactic latitudes below a certain energy threshold. Indeed, the apparent position of the principal image crosses the galactic equator at $E/Z \approx 133$ EeV in the left panel, $E/Z \approx 144$ EeV in the right, and the events in the secondary images are all below the energy of the caustic ($E/Z \approx 127$ EeV in the left panel, $E/Z \approx 108$ EeV in the right). Notice also that the divergence in the magnification at the caustic gives anyhow a finite number of events once it is convoluted with the differential spectrum of the incident CRs [7].

5. Conclusions

We have analysed flux magnification and multiple image formation in the galactic magnetic wind scenario put forward in [8]. In this scenario all observed arrival directions of EHECRs are compatible with a common origin in M87 if intergalactic magnetic fields provide the extra deflection (of order $20°$) needed to fine-tune the incoming particles in the appropriate direction as they enter the wind. We find that magnification factors well above 100 are attained in a significant energy range, with E/Z below 150 EeV. This 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.

One of the definite predictions of this model is the strong asymmetry expected 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, that will provide good coverage of the southern skies, will allow to check the viability of this model. In particular, a very strong suppression of events above $E \simeq 150$ EeV should be present at latitudes below $b \simeq -30°$ for the scenario to survive. Another general feature is that an abrupt kink in the overall spectrum should appear when the secondary images disappear, i.e. when the energy increases beyond the energy of the caustic crossing. Although no particular feature of this kind is apparent in the present data, an increased statistics in the northern skies would be desireable to definitely confront this prediction with observations.

As a final remark, we would like to point out that if a galactic wind is indeed present in the Milky Way, but with a smaller overall strength (so that for instance locally it is below the 2–3 μG amplitude of the spiral field which is inferred from observations, rather than the 7 μG adopted here), it could in any case have interesting observational consequences, especially if EHECRs have a component which is not light. In particular, one can think of a scenario in which an extragalactic source near the north pole, such as M87, produces heavy nuclei with $E > 10^{20}$ eV (and not necessarily protons at these energies), and their flux is strongly amplified by the galactic wind field. In this case a transition to a heavy composition could result at extremely high energies [2].

Acknowledgments

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[2] One would also have to take into account here that for propagation distances beyond ~ 10 Mpc the photodisintegration of nuclei out of the CMB photons starts to be important for $E > Z \times 10^{19}$ eV [3].

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