New all-sky map shows the magnetic fields of the Milky Way with the highest precision

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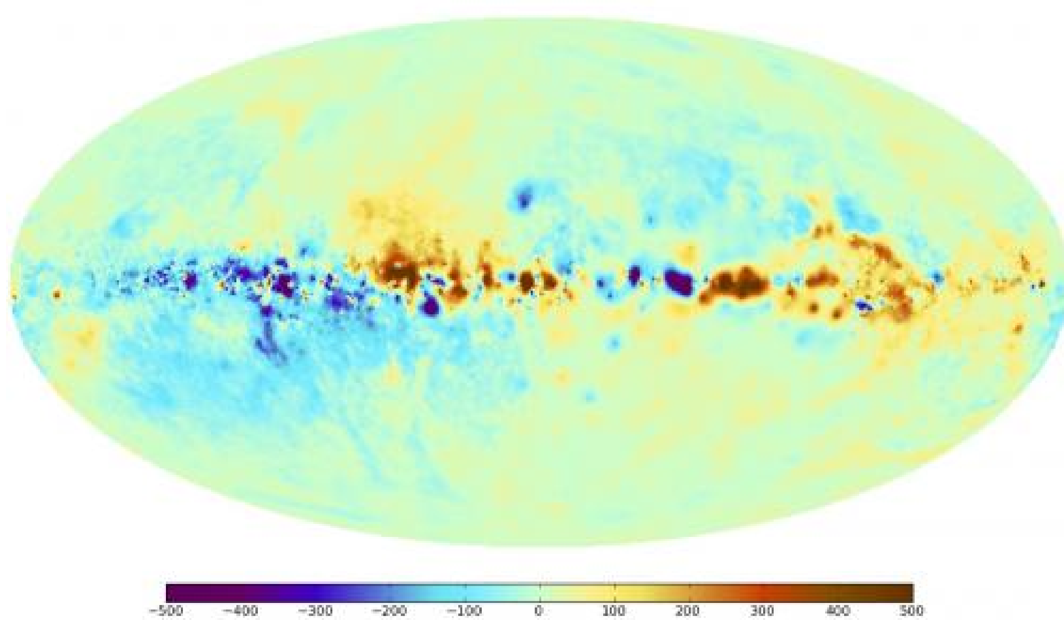

Fig. 1: The sky map of the Faraday effect caused by the magnetic fields of the Milky Way. Red and blue colors indicate regions of the sky where the magnetic field points toward and away from the observer, respectively. The band of the Milky Way (the plane of the galactic disk) extends horizontally in this panoramic view. The center of the Milky Way lies in the middle of the image. The North celestial pole is at the top left and the South Pole is at the bottom right.

(PhysOrg.com) -- With a unique new all-sky map, scientists at MPA have made significant progress toward measuring the magnetic field structure of the Milky Way in unprecedented detail. Specifically, the map is of a quantity known as Faraday depth, which among other things, depends strongly on the magnetic fields along a particular line of sight. To produce the map, data were combined from more than 41,000 individual measurements using a novel image reconstruction technique. The work was a collaboration between scientists at the Max Planck Institute for Astrophysics (MPA), who are specialists in the new discipline of information field theory, and a large international team of radio astronomers. The new map not only reveals the structure of the galactic magnetic field on large scales, but also small-scale features that provide information about turbulence in the galactic gas.

All galaxies are permeated by magnetic fields, including our own Milky Way galaxy. Despite intensive research, the origin of galactic magnetic fields is still unknown. One assumes, however, that they are built up by dynamo processes in which mechanical energy is converted into magnetic energy. Similar processes occur in the interior of the earth, the sun, and - in the broadest sense - in the gadgets that power bicycle lights through peddling. By revealing the magnetic field structure throughout the Milky Way, the new map provides important insights into the machinery of galactic dynamos.

One way to measure cosmic magnetic fields, which has been known for over 150 years, makes use of an effect known as Faraday rotation. When polarized light passes through a magnetized medium, the plane of polarization rotates. The amount of rotation depends, among other things, on the strength and direction of the magnetic field. Therefore, observing such rotation allows one to investigate the properties of the intervening magnetic fields.

To measure the magnetic field of our own galaxy, radio astronomers observe the polarized light from distant radio sources, which passes through the Milky Way on its way to the Earth. The amount of rotation due to the Faraday effect can be deduced by measuring the polarization of the source at several frequencies.

Each such measurement can only provide information about a single path through the Galaxy. To get a complete picture of the magnetic fields in the Milky Way from Faraday rotation measurements, one must observe many sources distributed across the entire sky. A large international collaboration of radio astronomers have provided data from 26 different projects to give a total of 41,330 individual measurements. On average, the complete catalog contains approximately one radio source per square degree of sky.

Even with so much data, coverage of the sky is still rather sparse. There remain large regions, especially in the southern sky, where so far only relatively few measurements have been made. Therefore, to obtain a realistic map of the entire sky, one must interpolate between the existing data points. Here, two difficulties arise. First, the respective measurement accuracies vary greatly, and more precise measurements should have a greater influence. Also, the extent to which a single measurement point can provide reliable information about its surrounding environment is not known. This information must therefore be directly inferred from the data itself.

In addition, there is another problem. The measurement uncertainties are themselves uncertain owing to the highly complex measurement process. It so happens that the actual measurement error for a small but significant portion of the data can be more than ten times as large as those indicated by the astronomers. The perceived accuracy of these outliers can strongly distort the resulting map if one does not correct for this effect.

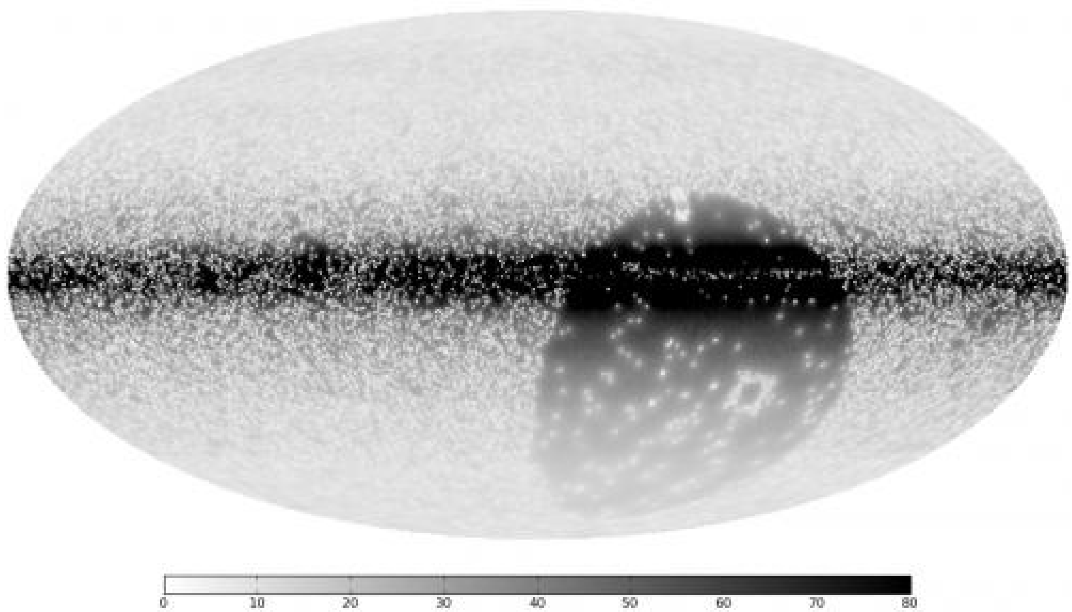

Fig. 2: The uncertainty in the Faraday map. Note that the range of values is significantly smaller than in the Faraday map (Fig. 1). In the area of the celestial south pole, the measurement uncertainties are particularly high because of the low density of data points.

To account for such problems, scientists at MPA have developed a new algorithm for image reconstruction called the "extended critical filter". To derive this algorithm, the team makes use of the tools provided by the new discipline known as information field theory. Information field theory incorporates logical and statistical methods applied to fields, and is a very powerful tool for dealing with inaccurate information. The approach is quite general and can be of benefit in a variety of image and signal-processing applications, not only in astronomy, but also in other fields such as medicine or geography.

In addition to the detailed Faraday depth map (Fig. 1), the algorithm provides a map of the uncertainties (Fig. 2). Especially in the galactic disk and in the less well-observed region around the south celestial pole (bottom right quadrant), the uncertainties are significantly larger.

To better emphasize the structures in the galactic magnetic field, in Figure 3 the effect of the galactic disk has been removed so that weaker features above and below the galactic disk are more visible. This reveals not only the conspicuous horizontal band of the gas disk of our Milky Way in the middle of the picture, but also that the magnetic field directions seem to be opposite above and below the disk. An analogous change of direction also takes place between the left and right sides of the image, from one side of the center of the Milky Way to the other.

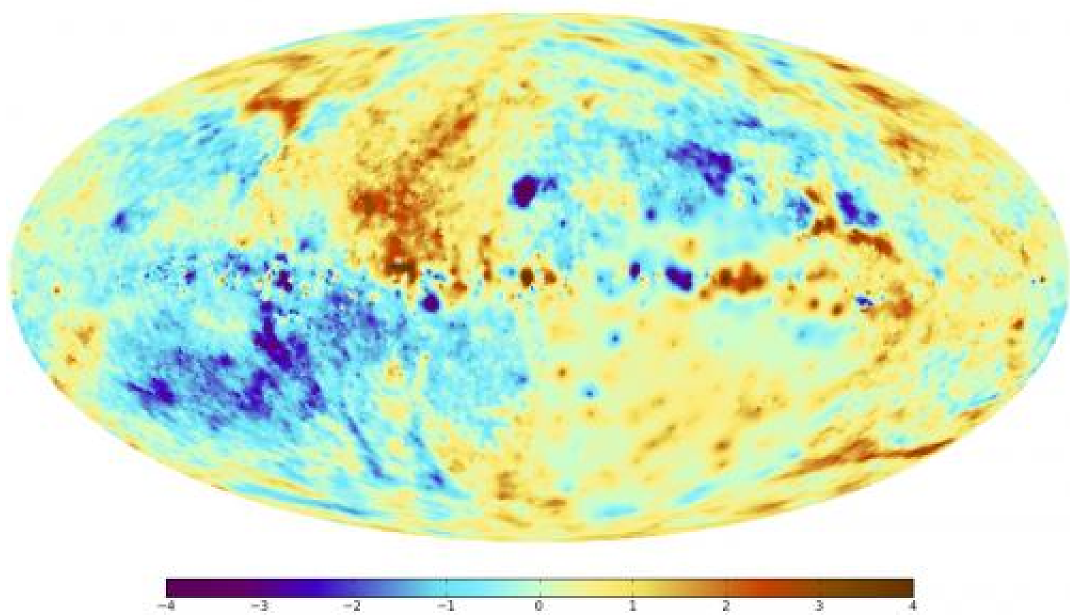

Fig. 3: In this map of the sky, a correction for the effect of the galactic disk has been made in order to emphasize weaker magnetic field structures. The magnetic field directions above and below the disk seem to be diametrically opposed, as indicated by the positive (red) and negative (blue) values. An analogous change of direction takes place accross the vertical center line, which runs through the center of the Milky Way.

A particular scenario in galactic dynamo theory predicts such symmetrical structures, which is supported by the newly created map. In this scenario, the magnetic fields are predominantly aligned parallel to the plane of the galactic disk in a circular or spiral configuration. The direction of the spiral is opposite above and below the galactic disk (Fig. 3). The observed symmetries in the Faraday map stem from our position within the galactic disk.

In addition to these large-scale structures, several smaller structures are apparent as well. These are associated with turbulent eddies and lumps in the highly dynamic gas of the Milky Way. The new map making algorithm provides, as a by-product, a characterization of the size distribution of these turbulent structures, the so-called power spectrum. Larger structures are more pronounced than smaller, as is typical for turbulent systems. This spectrum can be directly compared with computer simulations of the turbulent gas and magnetic field dynamics in our galaxy, thus allowing for detailed tests of galactic dynamo models.

The new map is not only interesting for the study of our galaxy. Future studies of extragalactic magnetic fields will draw on this map to account for contamination from the Galactic contribution. The next generation of radio telescopes, such as LOFAR, eVLA, ASKAP, Meerkat and the SKA, are expected in the coming years and decades, and with them will come a wealth of new measurements of the Faraday effect. New data will prompt updates to the image of the Faraday sky. Perhaps this map will show the way to the hidden origin of galactic magnetic fields.

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