Magnetic fields in our Galaxy and nearby universe

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The magnetic fields in our Galaxy and nearby universe are crucial knowledge to understand the origin and propagation of cosmic rays. Magnetic fields in our Galaxy have been most effectively revealed by Faraday rotation measures (RMs) of pulsars and background radio sources. In the Galactic disk, the large-scale magnetic field structure and field strength can be derived from pulsar RMs and Dispersion measures (DMs). From the sky distribution of RMs of extragalactic radio sources, the toroidal fields in the Galactic halo can be identifield from the antisymmetric distribution. To explore the magnetic fields of cosmological scale, the RMs in the Galactic pole regions can be used, because the foreground RM contribution from our Galaxy is minimized and can be eliminated easily. RMs have a larger deviations towards higher redshift, which is evidence for intergalactic magnetic fields. However, it is hard to disentangle it from the combination with unknown electron distribution in the intergalactic space.

1 Introduction

The first idea about the Galactic magnetic fields was proposed by Fermi [7] when he suggested the origin of cosmic rays from interstellar space and the acceleration by interstellar magnetic fields. Though Alfvén [2] insisted for the solar origin of cosmic rays, he first estimated the strength of Galactic fields amplified by motion of interstellar medium, $B \sim$ a few μG, which is correct, using the equipartition of magnetic field energy with motion of gas in the form of $B^2/8\pi \sim \rho v^2/2$ and adopting interstellar gas density $\rho \sim 10^{-24}$g cm^{-3} and typical gas velocity of 10 km s^{-1}. These are only very basic concepts on the extent and strength of Galactic magnetic fields.

At present, the new detection of ultrahigh energy (50 Eev) cosmic rays [1], which probably origin from AGNs in the nearby universe (<∼80 Mpc), leads to think about the magnetic fields in the intergalactic space. There is not yet helpful measurement on the the immediately intergalactic magnetic fields ourside our Galaxy, though "extragalactic magnetic fields" [4] have been detected in the nearby spiral galaxies and the intergalactic medium inside a few clusters of galaxies.

Our own Galaxy is so bright in sky not only in optical and radio bands, but also in the polarized radio sky [24,26] and the Faraday's sky or the Rotation Measure (RM) Sky which are closely related to the magnetic fields of our Galaxy. The RM sky is strikingly antisymmetric in the inner Galaxy [13]. Faraday rotation of polarized emission from a radio source ($*$) to us ($\oplus$) is defined by

$$\psi = 810 \int_{\oplus}^{*} \lambda^2(l) n_e(l) \mathbf{B}(l) \cdot d\mathbf{l}, \qquad (1)$$

here, ψ is total rotation angle (in rad), λ is wavelength (in m), $n_e(l)$ is intervening electron density (in cm^{-3}), $\mathbf{B}$ is vector magnetic field (in μG), and $d\mathbf{l}$ is the unit vector of the line of sight (in kpc) pointing towards us. Electron density and magnetic field vary along the line of sight. *To reveal the intervening magnetic fields, it is necessary to know the distribution of electron density along the line of sight.* For a cosmological radio source at a given location in the universe, e.g. at redshift z, the wavelength $\lambda(z)$ is also specifically related to observed wavelength by $\lambda_{\rm obs} = (1+z)\lambda(z)$. So, the rotation measure (RM, in rad m^{-2}) of a radio source at a redshift, z_s, should be defined as

$$RM_{\rm obs} = \frac{\psi_1 - \psi_2}{\lambda^2_{\rm obs1} - \lambda^2_{\rm obs2}} = 810 \int_0^{z_s} (1+z)^{-2} n_e(z)\ \mathbf{B}(z) \cdot d\mathbf{l}. \tag{2}$$

In different cosmological models, the dl and dz are related by

$$\frac{dl}{dz} = \frac{c}{H_0}(1+z)^{-1}[\Omega_{\rm m}(1+z)^3 + (1-\Omega_{\rm m}-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda]^{-1/2}. \tag{3}$$

Here, $H_0 = 100h$ km s^{-1}Mpc^{-1} is the Hubble constant, h is the dimensionless factor, c is the speed of light, $\Omega_{\rm m}$ is the dimensionless ordinary matter density, and Ω_Λ is the vacuum energy density. Most recent measurements [8,27] show that $h = 0.72 \pm 0.05$, $\Omega_{\rm m} \sim 0.3$ and $\Omega_\Lambda \sim 0.7$. Observed Faraday rotation consists of three contributions,

$$RM_{\rm obs} = RM_{\rm in} + RM_{\rm ig} + RM_{\rm fg}, \tag{4}$$

namely, the intrinsic rotation measure local to a source, $RM_{\rm in}$, the rotation measure from the intergalactic medium, $RM_{\rm ig}$, and the foreground RM from our Galaxy, $RM_{\rm fg}$. The foreground RM from our Galaxy are common contribution to RMs of radio sources located in a small sky region. To reveal the properties of intergalactic magnetic fields, the effect of intrinsic and foreground rotation measures should be eliminated from the observed values of $RM_{\rm obs}$.

2 Magnetic fields in our Galaxy

Pulsars in our own Galaxy emit polarized radio emission, and their RMs can be used to measure the interstellar magnetic fields [20]. Observed Faraday rotation of pulsars does not have any intergalactic contribution or intrinsic contribution, nor do we have to consider the cosmological effect on the wavelength. Therefore, the RM (in radians m^{-2}) of a pulsar at distance D (in kpc) can be simply given by $\mathrm{RM} = 810 \int_0^D n_e \mathbf{B} \cdot d\mathbf{l}$. Positive RMs correspond to the average fields directed toward us. In addition, the electron density between a pulsar and us can be measured by the pulse delay between the high and low radio frequencies. This is the dispersion measure (DM) of a pulsar, $\mathrm{DM} = \int_0^D n_e dl$. From the two observables, DM and RM, we obtain a direct estimate of the field strength weighted by the local free electron density,

$$\langle B_{||} \rangle = \frac{\int_0^D n_e \mathbf{B} \cdot d\mathbf{l}}{\int_0^D n_e dl} = 1.232\, \frac{\mathrm{RM}}{\mathrm{DM}}. \tag{5}$$

where RM and DM are in their conventional units of rad m^{-2} and cm^{-3} pc and $B_{||}$ is in μG.

Previous analysis of pulsar RM data often used the model-fitting method [17,19], i.e., to model magnetic field structures in the all paths from pulsars to us (observer) and fit them together with the electron density model to observed RM data. *Significant improvement* can be obtained now when RM and DM data are available for many pulsars in a given region with similar lines of sight. Measuring the gradient of RM with distance or DM is the most powerful method of determining both the direction and magnitude of the large-scale field in that particular region

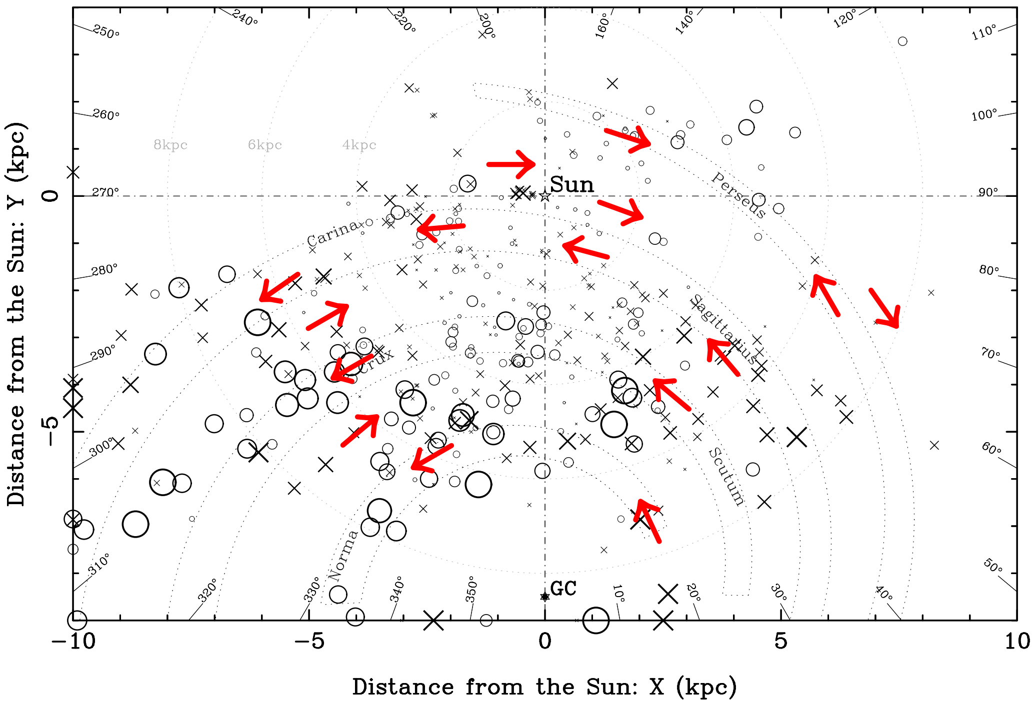

Figure 1: The RM distribution of 374 pulsars with $|b| < 8°$, projected onto the Galactic Plane. The linear sizes of the symbols are proportional to the square root of the RM values. The crosses represent positive RMs, and the open circles represent negative RMs. The approximate locations of four spiral arms are indicated. The large-scale structure of magnetic fields derived from pulsar RMs are indicated by thick arrows [15].

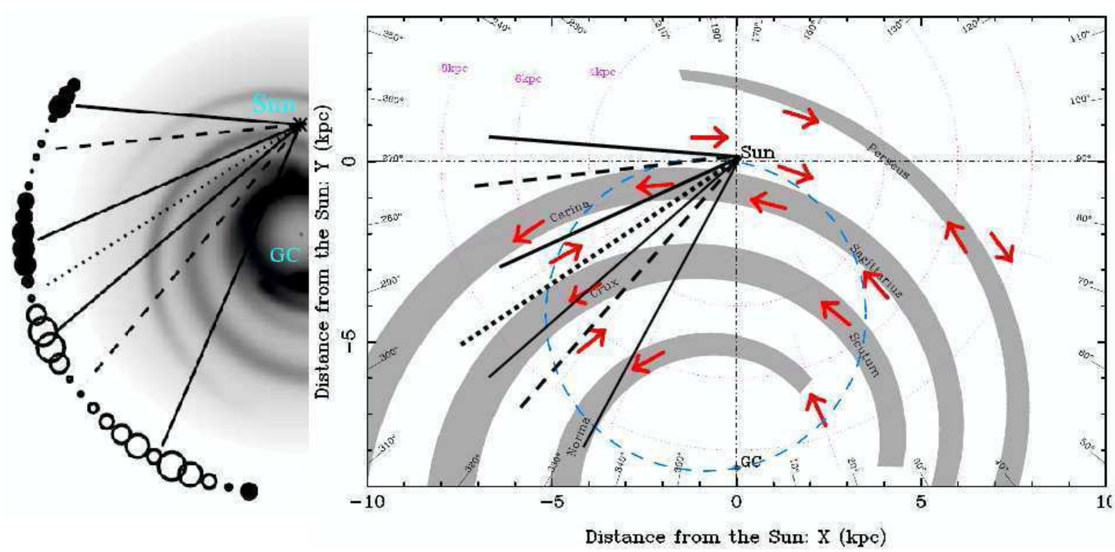

Figure 2: The general tendency of RM variations of extragalactic radio sources along the Galactic longitude, peaks and valleys [6], is very consistent with the large-scale structure of magnetic fields in the tangential regions derived from pulsar RMs [15].

of the Galaxy [21,15]. Field strengths in the region can be *directly measured* (instead of *modeled*) from the slope of trends in plots of RM versus DM. Based on Equation 5, we get

$$\langle B_{||}\rangle_{d1-d0} = 1.232\frac{\Delta \mathrm{RM}}{\Delta \mathrm{DM}} \tag{6}$$

where $\langle B_{||}\rangle_{d1-d0}$ is the mean line-of-sight field component in μG for the region between distances $d0$ and $d1$, $\Delta \mathrm{RM} = \mathrm{RM}_{d1} - \mathrm{RM}_{d0}$ and $\Delta \mathrm{DM} = \mathrm{DM}_{d1} - \mathrm{DM}_{d0}$.

Up to now, RMs of 550 pulsars have been observed [9,16,30,15]. Most of the new measurements lie in the fourth and first Galactic quadrants and are relatively distant, which enable us to investigate the structure of the Galactic magnetic field over a much larger region than was previously possible. We detected counterclockwise magnetic fields in the most inner arm, the Norma arm [14]. A more complete analysis for the fields near the tangential regions of the most probable spiral of our Galaxy [15] gives such a picture for the coherent large-scale fields aligned with the spiral-arm structure in the Galactic disk, as shown in Fig.1: magnetic fields in all inner spiral arms are counterclockwise when viewed from the North Galactic pole. On the other hand, at least in the local region and in the inner Galaxy in the fourth quadrant, there is good evidence that the fields in interarm regions are similarly coherent, but clockwise in orientation. There are at least two or three reversals in the inner Galaxy, probably occurring near the boundary of the spiral arms. The magnetic field in the Perseus arm can not be determined well. The negative RMs for distant pulsars and extragalactic radio sources [5] (see Fig. 1) in fact suggest the interarm fields both between the Sagittarius and Perseus arms and beyond the Perseus arm are predominantly clockwise. The average RM variation along the Galactic longitude of extragalactic radio sources [6], especially these of the fourth Galactic quadrant, are very consistent with the magnetic field directions derived from the tangential regions of the arms (see Fig. 2). This implies that the dominant contribution to RMs of extragalactic radio sources behind the Galactic disk comes from the interstellar medium mainly in tangential regions.

Stronger regular magnetic fields in the Galactic disk towards the Galactic Center have been suggested previously [18,28]. Measurements of the regular field strength in the Solar vicinity give values of 1.5 ± 0.4 μG [25,17,19], but near the Norma arm it is 4.4 ± 0.9 μG [14]. With significant more pulsar RM data now available, Han et al. were able to measure the regular field strength near the tangential points in the 1st and 4th Galactic quadrants [15], and then plot the dependence of regular field strength on the Galactoradii (see Fig. 3). Although uncertainties are large, there are clear tendencies for fields to be stronger at smaller Galactocentric radii and weaker in interarm regions. To parameterize the radial variation, an exponential function was used as following,

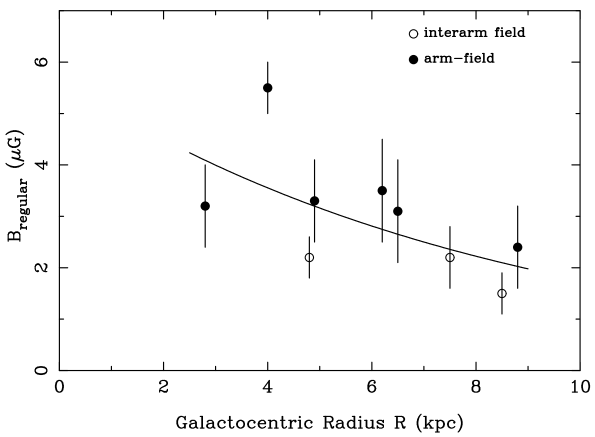

Figure 3: Variation of the large-scale regular field strength with the Galactocentric radius derived from pulsar RM and DM data near the tangential regions [15]. Note that the "error-bars" are not caused by the uncertainty of the pulsar RM or DM data, but reflect the random magnetic fields in the regions.

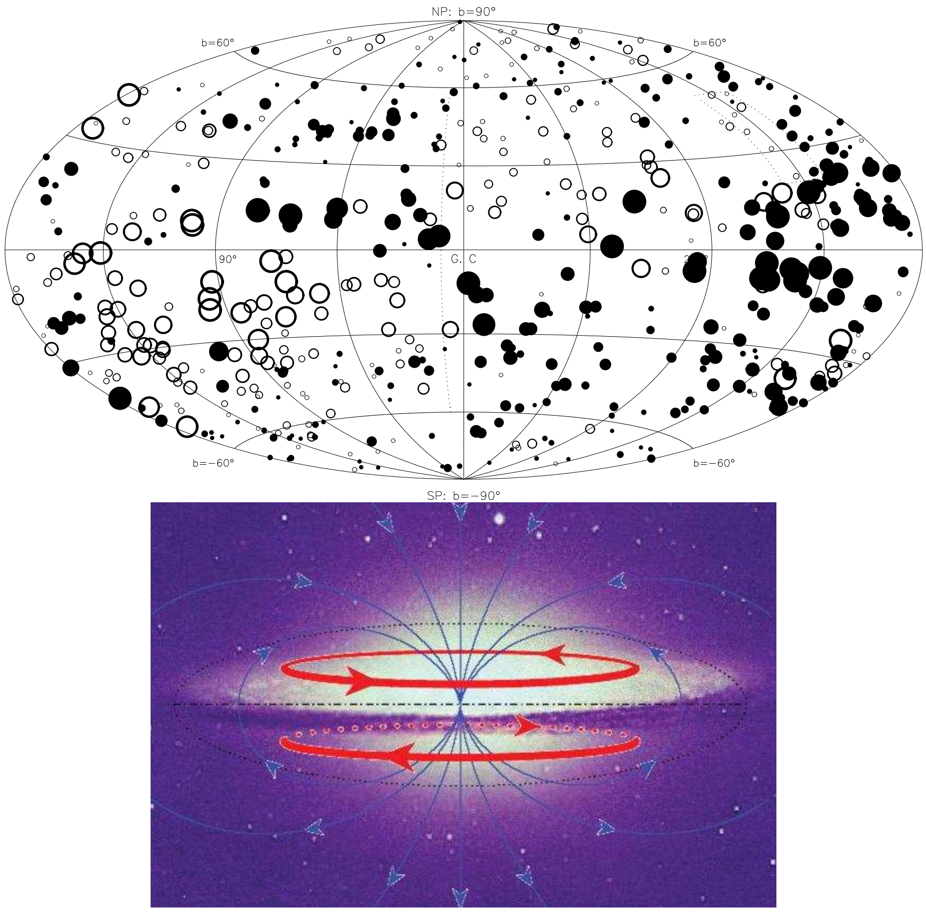

Figure 4: The antisymmetric rotation measure sky, derived from RMs of extragalactic radio sources after filtering out the outliers of anomalous RM values, should correspond to such a magnetic field structure in the Galactic halo as illustrated [13,16].

which not only gives the smallest χ^2 value but also avoids the singularity at $R = 0$ (for $1/R$) and unphysical values at large R (for the linear gradient). That is,

$$B_{\rm reg}(R) = B_0 \; \exp\left[\frac{-(R - R_\odot)}{R_{\rm B}}\right], \tag{7}$$

with the strength of the large-scale or regular field at the Sun, $B_0 = 2.1 \pm 0.3$ μG and the scale radius $R_{\rm B} = 8.5 \pm 4.7$ kpc.

The magnetic field structure in halos of other galaxies is difficult to observe. Our Galaxy is a unique case for detailed studies, since polarized radio sources all over the sky can be used as probes for the magnetic fields in the Galactic halo. As we mentioned before, the foreground RM from our Galaxy are common contribution to RMs of radio sources. That is to say, an "averaging process", which eliminates the random intrinsic RMs and discards the anonymous RMs, should be used to reveal the Galactic RM contribution. We removed any source if its RM value deviates from the average of their neighbours by 3 sigma, i.e. filtering out the outliers of RM values that is probably significantly from intrinsic RM, then from such a "cleaned" RM distribution in the sky, Han et al. identified the striking antisymmetry in the inner Galaxy respect to the Galactic coordinates [13,16]. This RM sky can result from the azimuth magnetic fields in the Galactic halo with reversed field directions below and above the Galactic plane (see Fig.4). Such a field can be naturally produced by an A0 mode of dynamo [31], and it is necessary to include this into any reasonable model for interstellar medium [29]. The observed filaments

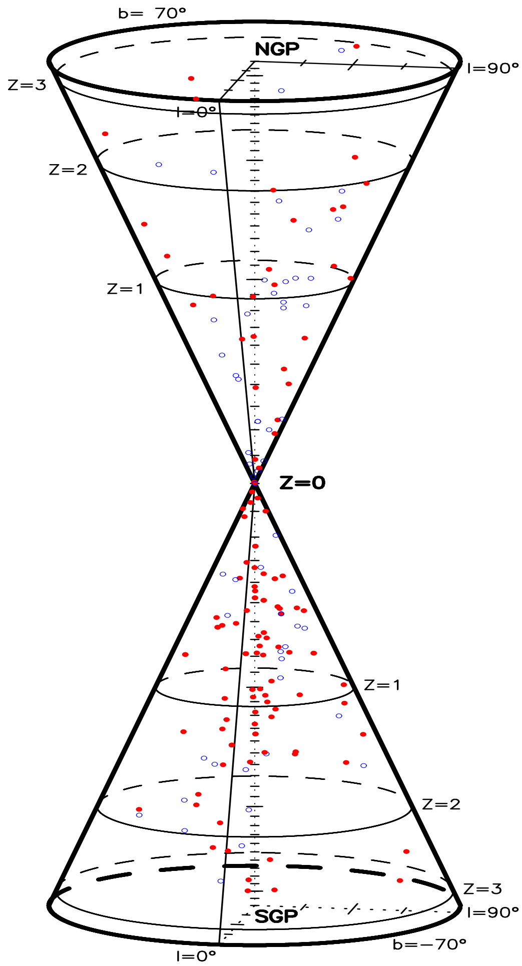

Figure 5: The space distribution of radio sources in the Galactic pole regions which we have their rotation measures observed. The red points stand for the positive RMs and blue ones for the negatives. It is clear that the rotation measures tend to be more positive (red) in the south Galactic pole and negative in the north pole, indicating the local vertical Galactic magnetic fields [12].

near the Galactic center should result from the dipole field in this scenario. The local vertical field component of $\sim$0.2 μG [17,16] may be related to the dipole field in the solar vicinity.

3 RM tomography for magnetic fields in the nearby universe

To probe the magnetic fields on cosmological scales, we have to look at the variation of RMs of radio sources with the redshift of the sources after the foreground Galactic RM contribution is eliminated. Three conditions have to be satisfied: 1). We have to measure the foreground RM sky to a certain level of accuracy. Looking at the RM sky in Fig.5, one can immediately see that the RMs near the two Galactic poles are on average very small. Whilst in other regions, the Galactic RMs are more difficult to assess accurately. A more extensive RM sky survey is required for this purpose. 2). To reveal the intergalactic RMs of a few rad m^{-2}, the measurements of each RM should be at least accurate to this level. With current technicques this is now acheivable using the wide-band spectral-polarimeters available at many radio telescopes. 3). The redshift of measured objects must also be known. This is now becoming possible for large numbers of sources by virtue of new large-scale optical spectrum survey, such as SDSS.

We have observed 110 objects with known redshift in the pole regions [12]. Together with previously published data, we found from RM data of two poles, see Fig. 6, that: 1). RM data clearly tend to have opposite signs which indicate a small but significant local vertical Galactic magnetic fields of 0.2 μG; 2) the deviations get larger at higher redshifts, which implies clearly that there is some kind of random RM contribution from intergalactic medium.

To understand the intergalactic magnetic fields, we still have three barriers to overcome. In each redshift range, we require a large number of objects with measured RMs, so that effect of their intrinsic RMs does not dominant. Second, we do not have enough information about the electron density distribution, such as whether it is clouded in the intergalactic space and how it couples with magnetic fields[32]. To delineate the intergalactic magnetic fields, there is still a long way to go.

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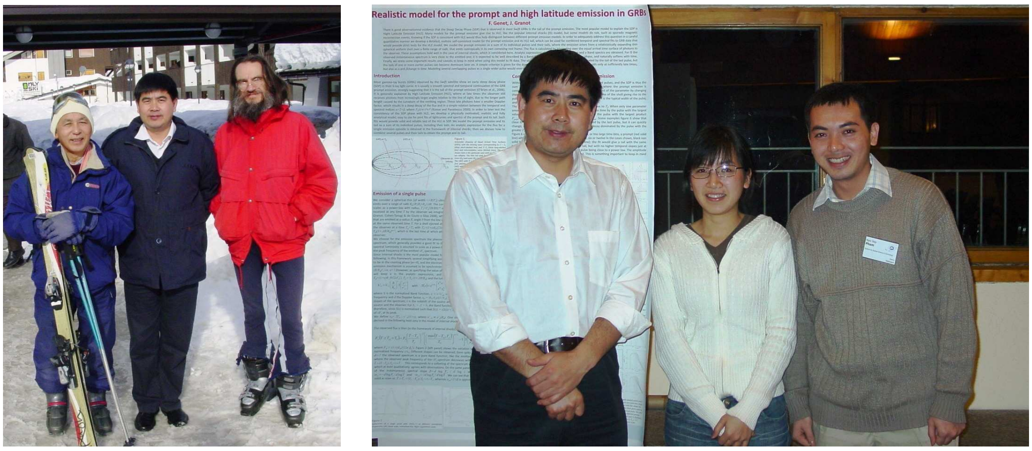

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