Observations of Galactic Magnetic Fields

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Abstract Radioastronomical methods are used to reveal the properties of Galactic magnetic fields. Their strength and regularity are derived from multi-wavelength observations of synchrotron emission and its percentage polarization. Faraday effects, which may cause depolarization and enhance the rotation measure of extragalactic sources, pulsars and supernova remnants, need to be taken into account. Rotation measures carry information on the magnetic field strength along the line of sight coupled to the warm interstellar medium. Recently, substantial progress has been made in Galactic polarimetry tracing magnetic fields on scales ranging from sub-pc to several hundred pc. This information is essential to understand the field properties on kpc scales, which at present is easier to be observed in nearby galaxies.

New results from polarization surveys and follow-up observations made with the Effelsberg 100-m telescope are discussed. Multi-frequency data show a highly structured magneto-ionic interstellar medium. Analysis of Faraday rotation effects probe the properties of the interstellar medium. Locally large magnetic field and thermal electron enhancements compared to average interstellar values are noted. High-frequency observations reveal the unusual properties of the poloidal magnetic field in the Galactic Center region. Polarized Galactic high latitude emission acts as a 'foreground' for observations of the cosmic microwave background and needs to be known at high frequencies.

1 Introduction

The emission at radio frequencies up to several GHz is mostly synchrotron radiation. Relativistic electrons moving in a magnetic field are deflected and convert a small fraction of their kinetic energy into radio emission. The strength of synchrotron radiation is highly dependent on the magnetic field strength, while its spectrum reflects the energy distribution of the radiating electrons, mostly well fitted by a power law. The orientation of the linear polarization shows the direction of the magnetic field, while its percentage is a measure of magnetic field regularity. Faraday rotation occurs when linearly polarized radiation passes through a magneto-ionic medium. The rotation measure (RM), defined as $\mathrm{RM}\,[\mathrm{rad/m^2}] = 0.81\,\mathrm{n_e}\,[\mathrm{cm^{-3}}]\ < \mathrm{B}_{||} >\ [\mu\mathrm{G}]\,\mathrm{l}\,[\mathrm{pc}]$, quantifies the Faraday rotation and carries physical information of the interstellar medium (ISM).

2 The Large-Scale Field

The magnetic field structure is at present known for a fairly large number of normal spiral galaxies (see the review of Beck (2001) and references therein). Galaxies seen face-on show the disk magnetic field to run along the spiral arms, whereas it is more regular in the interarm regions. Some galaxies show thick disk or halo emission when seen edge-on, whereas the polarized emission indicates the existence of magnetic fields up to kpc-distances from the disk. The most reliable observations of galaxies are from combinations of synthesis telescope data (e.g. VLA) with single-dish data from the Effelsberg 100-m telescope. However, despite of arcsecond angular resolution the spatial resolution is just of the order of a kpc and any small-scale structure is smoothed out.

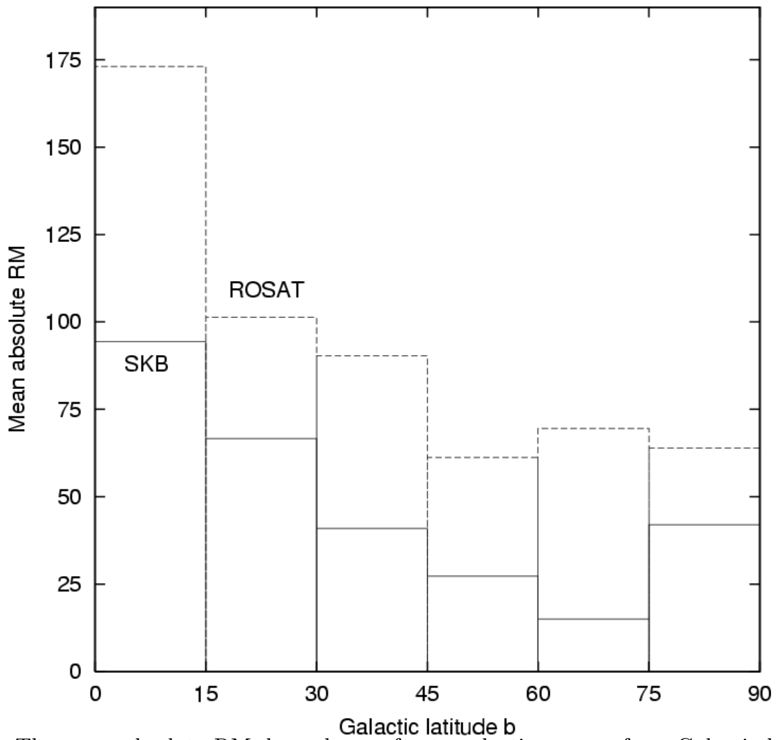

Fig. 1 The mean absolute RM dependence of extragalactic sources from Galactic latitude b. Extragalactic radio sources with detected X-ray emission by ROSAT (Reich et al., 2000) have higher RMs than those from the unbiased SKB-sample (Simard-Normandin, Kronberg & Button, 1982). The lower envelope of the SKB-sample is the Galactic contribution to the observed RMs.

Our position inside the Galaxy makes the determination of its global radio structure difficult. Beuermann, Kanbach & Berkhuijsen (1985) have deconvolved the 408-MHz all-sky survey of Haslam et al. (1982) with the additional assumption of a spiral arm pattern. They find a thin and a thick disk for the Galaxy with the magnetic field in the plane running along the spiral arms as expected. Its strength can be estimated by different methods and a smooth decrease from the inner Galaxy to its outer regions is indicated. In the solar vicinity a value for the total field strength of about 6 μG (Strong, Moskalenko & Reimers 2000) seems most likely. Although the global properties of the Galaxy are less well known than those for some nearby galaxies, parsec-scale objects can only be studied in the Galaxy because of much larger spatial resolution. Ideas on the generation and structure of large-scale magnetic fields can be proven that way.

3 Rotation Measures of Polarized Sources

Rotation measures (RMs) of distinct sources shining through the Galaxy are well suited to find the magnetic field properties along the line of sight. Extragalactic sources give data for the global magneto-ionic medium, while pulsars trace the medium within a few kpc

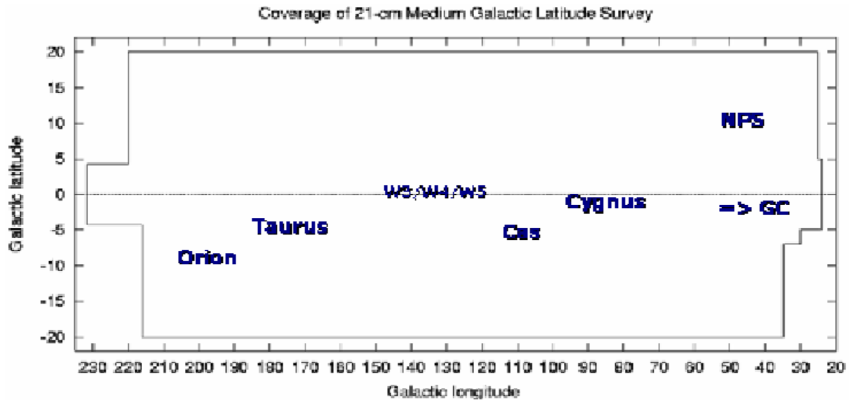

Fig. 2 The 'Effelsberg 1.4 GHz Medium Galactic Latitude Survey' area with some prominent regions indicated.

from the sun. While pulsars have no intrinsic RM that of extragalactic sources can be quite dominant. Fig. 1 illustrates differences of intrinsic RMs for two source samples: One with strong X-ray emission has systematically higher RMs than the other without any source selection. Thus a check of the source properties is needed, and in addition the source samples need to be sufficiently large. A detailed analysis and interpretation of available pulsar RM data was made by Han, Manchester & Qiao (1999) and Han (this volume). In brief, results for the magnetic field direction in spiral arms and systematic high-latitude variations of the Galactic magnetic field were derived and compared with dynamo model predictions.

4 Polarization Surveys of the Galactic Plane

Polarization observations of Galactic emission trace the magnetic field perpendicular to the line of sight and the percentage polarization is related to the regularity of the field. A series of polarization surveys up to high Galactic latitudes were carried out with the Dwingeloo 25-m telescope in the frequency range up to 1415 MHz (Brouw & Spoelstra 1976). They reveal a relatively smooth polarized emission and low RMs. This was somewhat expected from total intensity surveys showing smooth emission too. In consequence these results did not motivate more detailed polarization surveys. The Effelsberg 2.695 GHz survey measurements of the Galactic plane (Reich et al. 1984) simultaneously recorded polarized emission. These data were published by Junkes, Fürst & Reich (1987) showing patchy polarization related to the diffuse Galactic emission. These results, together with measurements from other telescopes, make it clear that the polarized Galactic emission is much more structured on small scales than previously believed.

Following the 2.695 GHz survey, which covers the Milky Way within 10°, the 'Effelsberg 1.4 GHz Medium Galactic Latitude Survey' was carried out for a 40° wide band including polarization (see Fig. 2 for details). This survey ran between 1994 and 2001 and needed about 1000 h of net-observing time. About 70% of the data have been reduced by now and the analysis of the first fields was made. The survey calibration onto an absolute scale and example maps of the survey showing the principal properties in various directions were already published by Uyanıker et al. (1998, 1999). These first maps are accessible via the web: `http://www.mpifr-bonn.mpg.de/survey.html`. Also a number of other surveys can be accessed from there.

In Fig. 3 one of the example maps in the Galactic anticentre is displayed. It shows rather smooth total intensity (with extragalactic sources superimposed) and highly structured linear polarization. Because the polarization structures have no distinct counterparts in total intensity they do not result from polarized emission regions, but reflect Faraday rotation and depolarization of polarized background emission, which in a complex way adds with emission from the foreground. Polarization vectors are rotated and/or scaled additionally and finally added to an unaffected vector. This way enhancements or depressions relative to the surroundings of the Faraday screen occur. It is also quite important whether the measurements are on an absolute or a relative scale. This makes a significant difference as shown in Fig. 5. Nevertheless, Faraday screens are a new powerful tool to investigate the magneto-ionic component of the interstellar medium.

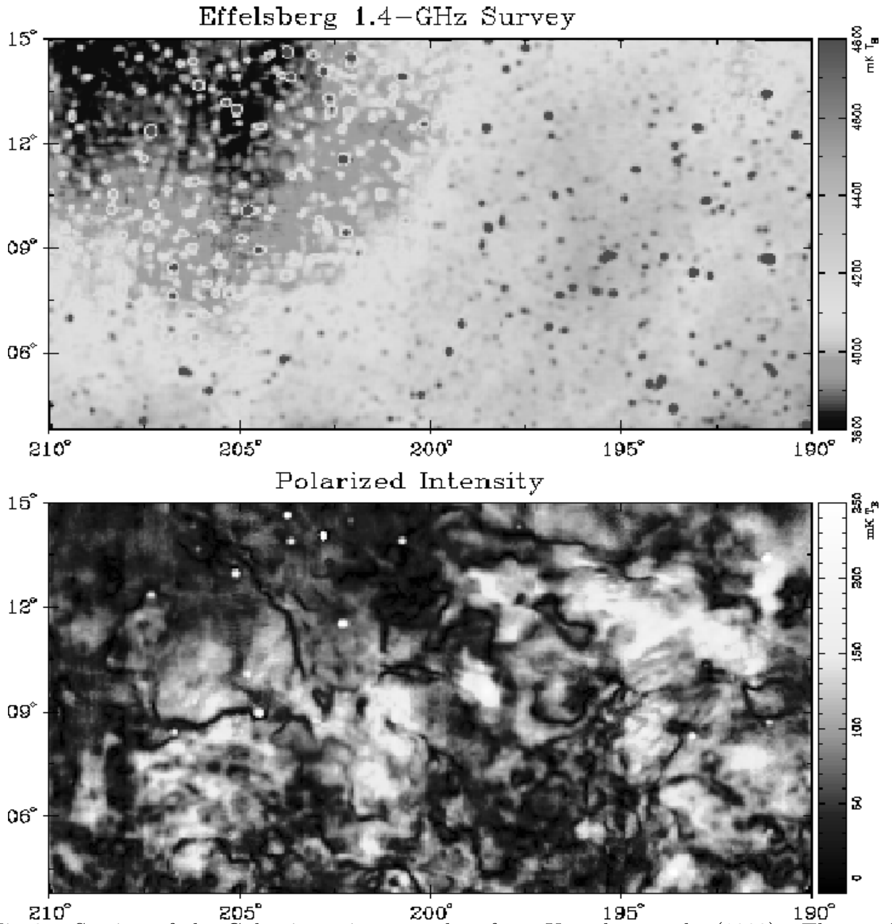

Fig. 3 Section of the Galactic anticentre taken from Uyanıker et al. (1999). The total intensities are rather smooth and rise towards the Galactic plane. Numerous extragalactic sources are superimposed (top). In contrast highly structured polarized intensities are seen with no relation to total intensity structures (bottom).

Towards the Galactic anticentre (Fig. 3) the observed polarization structures are more clearly pronounced than those seen towards the inner Galaxy (Fig. 4). This obviously reflects the difference in the length of sight. Towards the inner Galaxy structures rapidly change with frequency as is demonstrated in Fig. 4, where polarized regions visible at 1.4 GHz disappear at 2.7 GHz and new features show up at the higher frequency. This behaviour clearly indicates that a number of Faraday screens along the line of sight act at different distances.

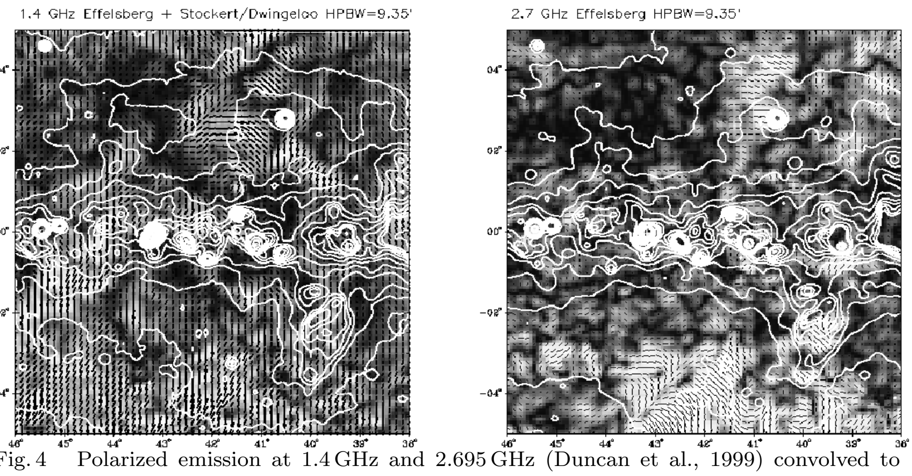

Fig. 4 Polarized emission at 1.4 GHz and 2.695 GHz (Duncan et al., 1999) convolved to 9.35' angular resolution. Contours show total intensities, with numerous intense sources concentrated along the Galactic plane. Polarized intensities (greyscale) and polarization E-vectors are superimposed.

Multi-frequency observations are needed for an analysis and decomposition. To reveal the intrinsic structure of the magnetic field at large distances high-frequency observations are essential, where RMs have decreasing influence.

4.1 Analysis of Faraday Screens

The most severe limitation in analysing the physical properties of Faraday screens is their unknown distance. A recent study of polarized emission from the Effelsberg 1.4 GHz survey towards the Taurus molecular cloud complexes showed clear relations and thus constrained the distance of Faraday screens (Wolleben, 2001). Adding 1.7 GHz observations an analysis of the Faraday screens was possible, and a number of high-RM structures at the surface of molecular clouds were investigated. The typical sizes of these Faraday screens are about 2 pc and RMs up to about 40 rad m^{-2} were derived. Excessive Hα emission is missing and also no excess of thermal radio emission is seen. The magnetic field strength along the line of sight must exceed 20 μG. It is not obvious which effect causes such strong magnetic field enhancements.

The determination of the polarized component up to a certain distance sets a lower limit for the synchrotron emission up to that distance for the case of a perfectly regular magnetic field. Towards the Taurus clouds with about 140 pc distance polarized emission ranging between 150 and 200 mK at 1.4 GHz at least implies about 300 mK for the total intensity. This is quite a large value and should be compared with previous estimates which give about 0.3 K/kpc. If this excess is not a local anomaly of the Taurus complex, it will affect Galactic synchrotron models (e.g. Beuermann, Kanbach & Berkhuijsen 1985), in particular by reducing the high latitude (halo or thick disk) emission.

5 High Latitude Polarization

Although RM on average decreases with Galactic latitudes (Fig. 1), Faraday screens on small scales are known to exist also at high Galactic latitudes (e.g. Wieringa et al. 1993; Haverkorn, Katgert & de Bruyn 2000; Reich et al. 2002). In Fig. 5 we display as an example an Effelsberg 1.4 GHz image of a $5^\circ \times 5^\circ$ large field at $l, b = 109^\circ, 73^\circ$ (Reich et al. 2002). Polarized emission features on scales up to about 1° are visible on the Effelsberg

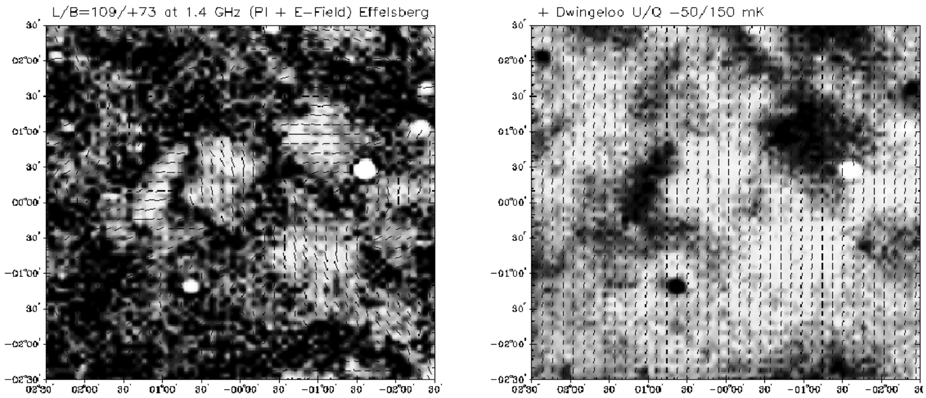

Fig. 5 Polarized high latitude emission at 1.4 GHz. The left image shows an Effelsberg map with relative zero levels in Stokes U and Q. The right map has added large-scale structures as taken from the Dwingeloo survey (Brouw & Spoelstra, 1976).

map. They are not correlated to total intensity enhancements or depressions and therefore are acting as Faraday screens affecting polarized background emission. These features are not characterised by excessive Hα emission (although deep observations are missing) that an upper limit for the thermal electron column density is set by the noise in the radio continuum image.

It is rather important to add the large-scale smooth emission to the Effelsberg image, which is on a relative level due to zero-level definition at the edges of the map. The absolutely calibrated large-scale emission is estimated from the Dwingeloo survey of Brouw & Spoelstra (1976). For the field displayed in Fig. 5 the large-scale component dominates by more than 90% (although limitations in the Dwingeloo survey imply about 30% uncertainties). However, different to total intensities the inclusion of large-scale structures is not a simple addition as for total intensities but a vector addition by adding Stokes U and Q which may have different signs. Thus features in the Effelsberg map become *enhanced* or *depressed*, depending on their vector orientation relative to the main field direction. The actual amount of RM imposed by the Faraday screen depends on its distance and the relative strength and magnetic field direction of the foreground and background emission components.

5.1 Influence on the Cosmic Microwave Background Emission

Cosmic microwave background (CMB) experiments have nowadays sensitivities to study details of CMB fluctuations. The angular power spectrum derived from these experiments reflects the evolution of the early universe. CMB studies have to take into account the Galactic foreground. Contamination by the rather smooth synchrotron emission observed in cold high Galactic latitudes does not seem to be a serious limitation. Possibly undetected flat-spectrum extragalactic sources may be problematic. However, the next generation of CMB experiments will include studies of the polarized fluctuations to decide on cosmological models. These signals are much fainter than total intensity fluctuations. Extrapolations of angular power spectra of the polarized emission indicate that measurements up to about 60 GHz might be affected by the Galactic foreground (Tucci et al. 2000). However, the large unknown in these estimates is the amount of Faraday rotation, which obviously distributes power from large scales into small scales. As discussed above, Faraday screens even act at very high Galactic latitudes so that new high-frequency measurements are needed. It is planned to use the Urumqi 25-m telescope for 5 GHz polarization measurements to be combined with Effelsberg 1.4 GHz polarization data at the same angular resolution. This way it is expected to significantly improve predictions for the polarized Galactic foreground at high frequencies.

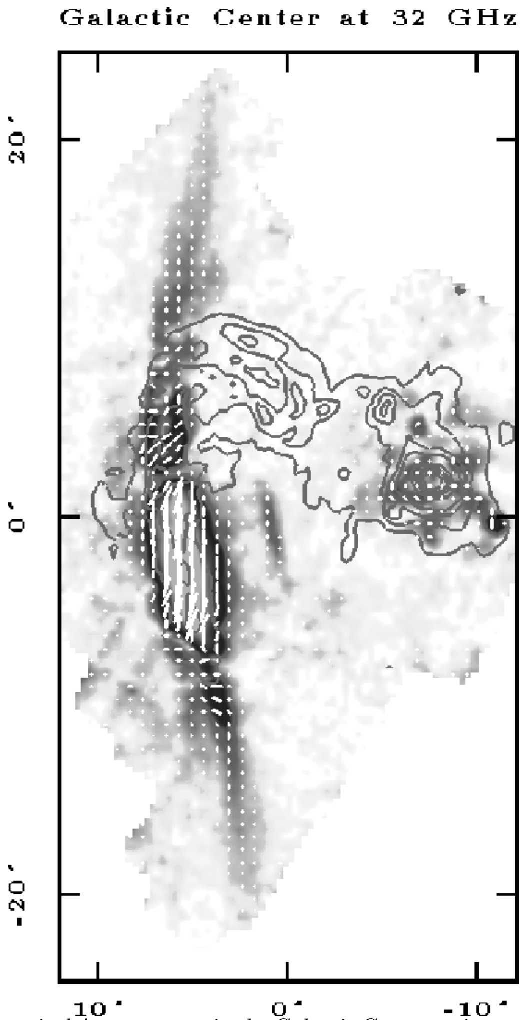

Fig. 6 The vertical Arc structure in the Galactic Centre region traces a strong poloidal magnetic field as seen by high-frequency observations. Very high RMs ranging up to several thousand rad m^{-2} were derived. The magnetic field strength of the Arc is a few hundred μG in the diffuse and up to 1 mG within its narrow filaments. The 32 GHz image is from the Effelsberg 100-m telescope convolved to an angular resolution of 36" (Reich, in prep.). The Sgr A emission complex is located west to the Arc and shows weak but rather complex polarization. The Galactic coordinates are relative.

6 The Magnetic Field in the Galactic Center Region

The magnetic field in the Galactic Center deviates largely from that in the Galactic disk. Strong and very thin synchrotron filaments were detected, which trace a vertical magnetic field. Its strength has been estimated to be one or two orders of magnitude larger than in the Galactic disk. Fig. 6 displays an Effelsberg 32 GHz image. This frequency is high enough to observe the polarized Galactic Center emission without being largely affected by depolarization. Most of the numerous filaments are visible only at low frequencies as they have a rather steep spectrum, except for the most intense Arc structure which was shown to have a flat or even inverted spectrum (Reich et al. 1988). Recently, enhanced 150 GHz emission was detected from that part of the Arc (Reich, Sofue & Matsuo 2000), which is in interaction with the molecular cloud G0.108-0.108 (Tsuboi, Ukita & Handa 1997). Here the most energetic particles show up. Magnetic reconnection at the surface of the molecular cloud moving perpendicularly to the strong vertical field is proposed as the most likely acceleration process for a quasi-monoenergetic electron spectrum, which is required to illuminate the Arc (Reich, Sofue & Matsuo 2000).

7 Summary and Outlook

The analysis of polarized synchrotron emission is a powerful tool to study magnetic field structures and the magneto-ionic component of the interstellar medium. Large-scale surveys are on the way and these trigger follow-up measurements at high frequencies to investigate the nature of Faraday screens. Additional data are needed to constrain their distance. Sensitive measurements are required to estimate the amount of thermal electron densities. The results obtained so far indicate strong local enhancements of magnetic fields and/or electron densities in the interstellar medium. Their origin largely seems unknown so far. Beyond the properties of the Galactic emission these investigations are also relevant to estimate the foreground influence on sensitive CMB studies. Future observational needs are absolutely calibrated polarization measurements, which require substantial efforts, and extensions of systematic surveys towards higher frequencies.

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