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C. R. Physique 4 (2003) 901–908
COMPTES RENDUS PHYSIQUE

The Cosmic Microwave Background/Le rayonnement fossile à 3K

Galactic emissions: seeing through the Galaxy

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Presented by Guy Laval

Abstract

The diffuse matter in our Galaxy is certainly to be damned by the cosmologist because it pollutes the CMB sky with the various emissions from its components: dust, ionised gas (free–free) and energetic particles (synchrotron). We detail here our knowledge, but also the unknowns, regarding these radiation sources. As we are not in a position to be able to physically escape our Galaxy, the better knowledge of these foreground components is our only hope to build a consistent model which will at least allow us a virtual escape. However, the detailed understanding of the physics of the different emissions and of the large scale distribution of the various emitters is a delight for many of us. We will show here some aspects, with a peculiar emphasis on a possible emission from tiny rotating grains. ***To cite this article: M. Giard, G. Lagache, C. R. Physique 4 (2003).***

Résumé

Les émissions galactiques : observer à travers la galaxie. La matière diffuse de notre Galaxie est certainement l'un des cauchemars du cosmologiste car elle pollue la mesure du fond cosmique primordial par l'émission de ses divers constituants : la poussière, le gas ionisé (rayonnement libre–libre) et les particules énergétiques (synchrotron). Dans cet article nous détaillons les connaissances actuelles mais aussi les incertitudes, concernant ces sources d'émission. Puisque nous ne sommes pas en mesure de pouvoir sortir physiquement de notre Galaxie, une meilleure connaissance de ces componsantes d'avant-plan sera notre seul espoir d'effectuer au moins une sortie virtuelle dans le but de réaliser une mesure du fond cosmique de grande précision. Toutefois, la compréhension détaillée de la physique des différentes émissions, ainsi que la distribution à grande échelle des diverses sources est un délice pour beaucoup d'entre nous. Nous en montrons ici quelques aspects, en détaillant plus particulièrement la possible émission millimétrique des tous petits grains en rotation. ***Pour citer cet article : M. Giard, G. Lagache, C. R. Physique 4 (2003).***

Keywords: Cosmic Microwave Background anisotropies; Cosmology; Early Universe

Mots-clés : Anisotropies du fond de rayonnement cosmique ; Cosmologie ; Univers primordial

1. Introduction

Although this is a faint light that you might be able to catch by eye only on dark nights and under clear skies, our Milky-Way is the dominant source of emission at the frequencies of the CMB radiation. This is illustrated in Fig. 1, where we show the full sky at visible and radio wavelengths, in a projection where the Milky-Way stands in the middle of the figure. At visible wavelengths most of the hundred billions of stars of our Galaxy are actually hidden by tiny opaque dust particles which are spread among the gas between the stars, drawing dark lanes along the Milky-Way. This is not the case at CMB wavelengths in

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1631-0705/$ – see front matter
doi:10.1016/j.crhy.2003.09.009

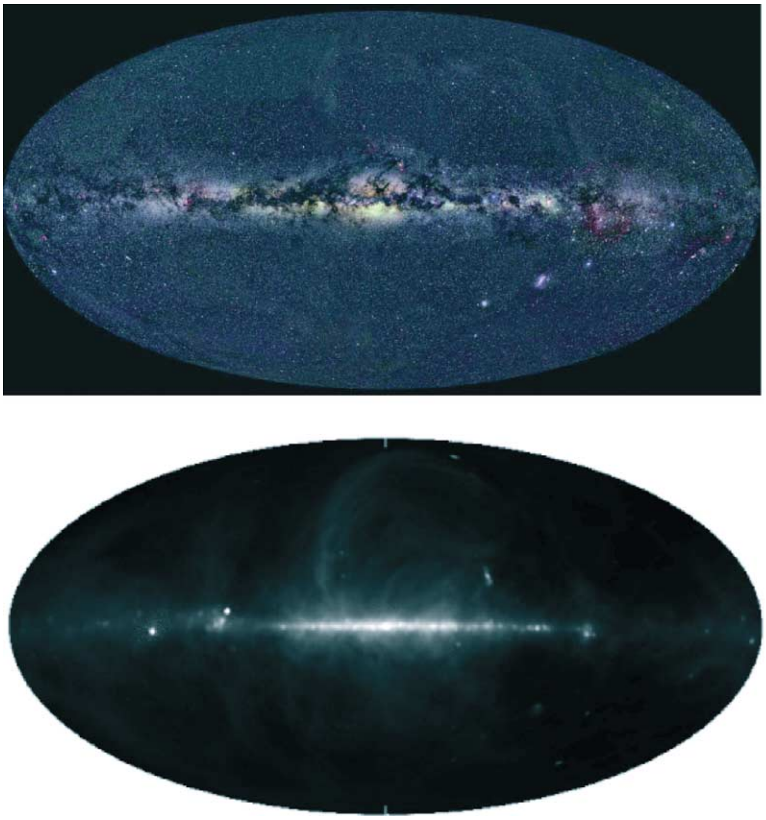

Fig. 1. All sky projection of the celestial sphere. Upper: visible electromagnetic radiation showing the stars in the sun neighborhood and dusty dark clouds along the Milky-Way (reproduced from A. Mellinger WEB site: http://canopus.physik.uni-potsdam.de/~axm/astrophot.html). Lower: radio sky at 408 MHz from Haslam et al. [1] showing the synchrotron emission from relativistic particle trapped in the Galactic magnetic field.

the radio range where the dust particles become transparent, allowing us to probe the full Galaxy. The bright features which cover the whole sky at these wavelengths are emissions from the interstellar matter composed of gas, dust and energetic particles confined in a thin rotating plate. However, as we ourselves stand within this plate, the full gaseous Milky-Way is shining in all directions with a sharp brighter feature along the line which is drawing the galactic plane around us in the sky.

2. The three 'well-known' components

The different particles in the interstellar medium emit electromagnetic radiations with various energy distributions. This is shown in Fig. 2 where we have plotted the typical brightness of the different sources of emission at high and low galactic latitudes (respectively apart and within the Milky-Way). The high frequency part of the spectrum, $\nu > 90$ GHz, is dominated by the thermal emission of dust particles having temperatures ranging from 10 to 100 K. The lower frequencies are dominated by the thermal radiation from the hot ionized gas (free–free) and the synchrotron emission of energetic particles trapped in the Galactic magnetic field. As shown in Fig. 2 the dust emission increases with frequency, whereas the other two exhibit a negative slope. We will omit in this review the rotation emissions from interstellar molecules as carbon monoxyde (CO) at 115.38 and 230.77 GHz. Those are used to probe the dense molecular regions of the interstellar medium, but they are very narrow in frequency (0.1 GHz maximum) so that their total flux will hardly pollute CMB measurements performed in broad frequency bands (more than 10 GHz wide).

The different spectral behaviours of the three foregrounds allow us to recover each one from a set of measurements of the same sky direction in different wavelengths bands (i.e., frequency bands). This is very useful, first to study the distribution of the different emission sources in the Galaxy, but also to recover properly the background emissions of the more distant Universe: CMB, galaxies, etc.

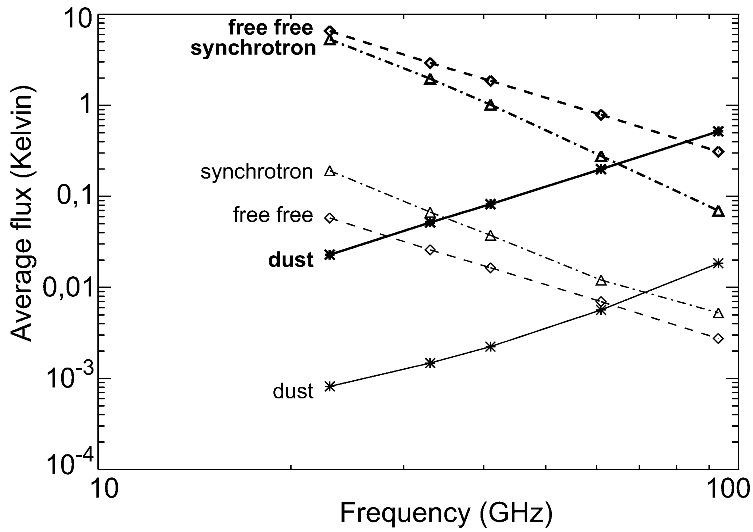

Fig. 2. Average sky brightness of the different galactic continuum emissions at CMB wavelengths: dust (full line), free–free (dashed), and synchrotron (dot-dashed). Thick lines are obtained for the directions on the sky along the plane of the Milky-Way ($|bII| < 1°$); Thin lines show the value for directions out of the galactic plane ($|bII| > 10°$). This has been computed from the component separation performed on the WMAP satellite data by Bennett et al. [2]. The flux units are physical temperatures of the equivalent blackbody in Kelvin, which means that the intensity of the CMB would be 2.73 K at all wavelengths.

We show in Fig. 3 the maps of the separated emissions from dust, free–free and synchrotron. These have been estimated from the multi-frequency measurements of the WMAP satellite between 23 and 94 GHz (see Bennett et al. [2]).

2.1. Dust

Small dust particles with sizes ranging from a nanometer to a fraction of micrometer are ubiquitous in the interstellar medium. They result from the natural condensation of heavy elements produced by the nucleosynthesis in stars and released to the diffuse medium in late type stars and supernovae explosions. Although they are by mass only a minor component (about 1%, hydrogen and helium accounting for 99%), they can fully stop the UV and visible radiation from stars. The physical reason for this very efficient opacity lies in the simple fact that the large bounded structures of those small solids allow some of the electrons to be much more mobile than what they can be in single atoms or small molecules: e.g., π electrons in aromatic carbon rings and conducting electrons in metallic crystals. Interstellar grain models have been improved for 30 years in order to fit all observational constraints: UV, visible and infrared absorption properties, X ray scattering, infrared emission, polarisation properties of the absorbed and emitted light, and elemental abundances of the heavy elements. These models are made of carbon and silicate grains with varying crystalisation degrees: diamond, graphite and amorphous carbon for the former; crystaline to amorphous silicates for the later. For details see Désert et al. [3], and more recently Li and Draine [4].

The star light absorbed by the grains is converted to infrared energy that the grains radiate as thermal emission. The integrated dust flux in a peculiar direction of the sky, as shown in Fig. 3 is the integral on the line of sight of the dust emission. It is then a complex function of the star light and the dust density on the line of sight. As a consequence most of the bright spots in Fig. 3 are giant star forming regions, where thousands of newly formed stars are kept hidden in their obscuring parent molecular cloud. However we are able to catch the infrared dust emission of their surroundings. The study of such a map tells us a lot about the star formation activity throughout the galaxy. A detailed analysis of a star forming complex such as the one performed by Boulanger and Perault [5] on the Orion region demonstrates that more than 50% of the light from the new and massive stars succeeds to escape from the parent cloud and is the major heating source for the dust spread in the very diffuse medium away from all stars. This is why, in addition to the strong sources concentrated in the Galactic plane, the dust emission illuminates the whole sky, making a haze which definitively pollutes the faint background fluctuations of the CMB.

2.2. Free-free

The free–free radiation is one of the main thermal emissions of astrophysical plasmae. It results from Coulomb interactions between the free electrons and the ions. Its energy distribution extends continuously from the near infrared to the radio electromagnetic ranges. Its physical description is much more reliable than that of the dust detailed above, and the formulae

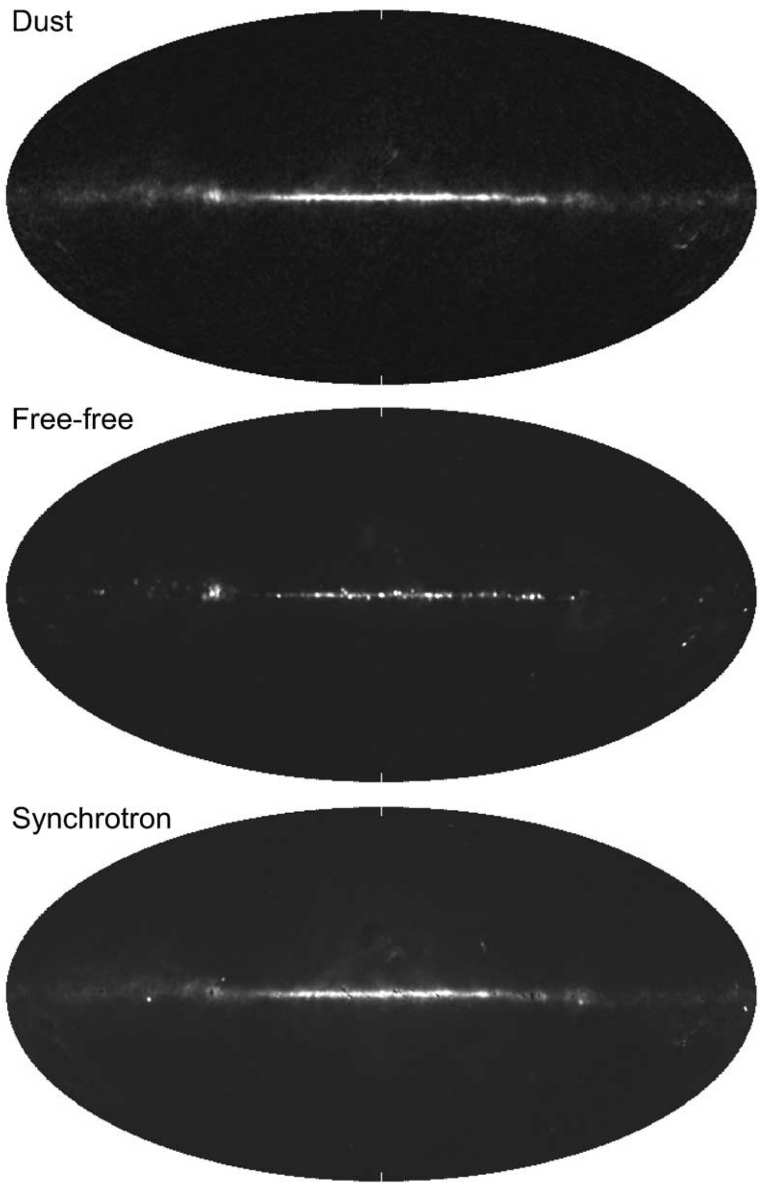

Fig. 3. Full sky maps of the foreground emission separated from the multi-frequency measurements of the WMAP satellite: dust (upper), free–free (middle) and synchrotron (lower).

relating the gas parameters (temperature, density and thickness) to the measured flux can be found in basic astrophysics books such as Lang [6] or Spitzer [7].

Similarly to the dust emission, the free–free map (that can be obtained from sky surveys of the H_α hydrogen emission line), clearly shows bright spots concentrated in the galactic plane, corresponding to dense ionised gas around newly formed stars (HII regions), and a diffuse emission due to the ionized surfaces of the neutral clouds which fill a large fraction of the Milky-Way. These surfaces are actually rather to be understood as a very intricate mixing of ionized and neutral gas, since observations have shown that the density structure of the interstellar medium is of the fractal type over several decades of scale sizes (see, e.g., the fractal structure of molecular clouds in Elmegreen and Falgarone [8]).

Comparative studies of free–free and dust emission can bring important information on the hardness of the interstellar radiation field in different places of the Galaxy because their sources are not sensitive to the same photon energies. The excitation of the ionised gas being dominated by the physics of hydrogen ionisation, free–free emission traces photon energies higher than the hydrogen ionisation potential: 13.6 eV. On the contrary, the dust is heated by photons of all energies: above and below

13.6 eV. The massive stars, O and B types, being responsible for the harder photons, the free–free to dust comparison should be able to inform the astrophysicist on the high mass end of the star formation activity all over the Milky-Way.

2.3. Synchrotron radiation

The very massive stars (⩾8 solar masses) die in supernova explosions which are able to accelerate electrons and ions to relativistic speeds. Those get trapped in the galactic magnetic field. The synchrotron emission visible at the lower CMB frequencies is dominated by the emission from electrons spiraling around galactic magnetic field lines. The frequency spectrum of the synchrotron emission is thus related to the energy distribution of the relativistic electrons and the strength of the magnetic field. This emission lacks actually a precise knowledge. Before the recent release of the WMAP satellite result, the low frequency radio continuum survey at 408 MHz by Haslam et al. [1] was probably its best guess. However, the comparison of the WMAP synchrotron estimate, which is shown in Fig. 3, is significantly different from the 408 MHz measurement. This can be a consequence of the very different frequencies of the two templates, and of variable electron energy distributions in different places over the Galaxy. To progress in the knowledge of the distribution of relativistic electrons in the Milky-Way we will thus need sensitive surveys in the 1 to 20 GHz range. The problem in the synchrotron emission might actually be linked to additional sources of foreground emission in this wavelength range which are usually referred to as the *anomalous microwave emission*. We will discuss this in the following section.

3. The anomalous microwave emission

Cross-correlations of CMB data with far-infrared (dust-dominated) maps have revealed the existence of a microwave emission component with spatial distribution traced by these maps. This component has a spectral index suggestive of free–free emission and so has been first interpreted as free–free emission (Kogut et al. [9]). However, Kogut [10] showed in small parts of the sky that were covered by H_α data that the microwave emission was consistently brighter than can be explained solely from free–free emission traced by H_α. This is confirmed more recently by Banday et al. [11] also using *COBE/DMR* data. Thus, the correlated component cannot be due to free–free emission alone. Moreover, it is also well in excess and spectrally very different from what is expected from thermal dust emission and synchrotron radiation. Due to its mysterious nature, this component has been called the 'anomalous microwave emission'. The identification of this foreground, followed by its modelisation, is still a major challenge both for galactic studies and CMB analysis.

Recent works suggest that this anomalous far-infrared correlated component originates from spinning dust grain emission (Draine and Lazarian [12], De Oliveira-Costa et al. [13]), tentatively detected at 5, 8 and 10 GHz by Finkbeiner et al. [14]. The rotational emission is proportional to the fourth power of the angular velocity. Only extremely small dust grains rotate sufficiently rapidly to produce a non negligible emission. Draine and Lazarian [12] and Li and Draine [4] estimate the size distribution of ultrasmall grains, their dipole moments and their rates of rotation and predict levels of the microwave emissivity. They came out with the conclusion that the electric dipole radiation could explain the anomalous component. An alternative explanation for the anomalous component is provided by thermal fluctuations in the magnetization of interstellar grains causing magnetic dipole radiation (Draine and Lazarian [15]). However, this requires that the interstellar grains consist in part of magnetic material, such as metallic Fe or magnetite Fe_3O_4.

However, the previous detections/interpretations of the anomalous component has not been confirmed by the first analysis of *WMAP* data. Very recently, Bennett et al. [2] using *WMAP* data do not find any evidence for the anomalous microwave emission that is limited to $<5\%$ of the 9.1 mm foreground emission. Their foreground component model comprises only free–free, synchrotron and thermal dust emission, and the observed galactic emission matches the model to $<1\%$. In their analysis, most of the emission of the anomalous component is attributed to synchrotron radiation. Unlike in Bennett et al. [2], an analysis of the galactic contributions to the millimeter sky, based on *WMAP* data combined with several templates of dust emission (*DIRBE/COBE* and *FIRAS/COBE*), do find evidence for a residual microwave emission, over free–free, synchrotron and far-infrared dust emission (Lagache [16]). This work focuses only on the high latitude regions where the results are easier to interpret in term of physical properties of dust and where CMB analysis are performed. Since the HI-correlated dust emission is the dominant component at high galactic latitude at infrared/far-infrared/submillimeter wavelengths,[1] they compute the emission spectrum of the dust/free–free/synchrotron components associated with HI gas from low to large column densities. They find a significant residual *WMAP* emission over the free–free, synchrotron and the dust contributions from 3.2 to 9.1 mm that: (1) exhibits a constant spectrum from 3.2 to 9.1 mm; and (2) significantly decreases in amplitude when $N_{\rm HI}$ increases,

[1] Except in the very low HI column density regions where the Cosmic Infrared Background becomes an important contribution, e.g., Lagache and Aghanim, this issue.

contrary to the HI-normalised far-infrared emission, which stays rather constant. It is thus very likely that the residual *WMAP* emission is not associated with the Large Grain dust component whose emissivity is rather constant in the very diffuse medium. The decrease in amplitude with increasing opacity resembles in fact to the decrease of the transiently heated dust grain emission observed in dense interstellar clouds. This is supported by an observed decrease of the HI-normalised 60 µm emission with HI column densities. On the possible models of the 'anomalous microwave emission' linked to the small dust particles are the spinning dust (as described above) and the excess millimeter emission of the small grains. The small grains are transiently heated when an ultraviolet photon is absorbed. The mean interval between successive ultraviolet photons is longer than the cooling time and thus, between 2 impacts, the temperature of the particles is very low (but is at least the CMB temperature). Such particles could therefore emit significant emission in the millimeter channels.

In conclusion, the so-called 'anomalous microwave emission' seems to be linked to the small interstellar dust grains. Due to the unknown properties of the small particles, the models of possible millimeter emission of these particles have large uncertainties. Substantial progress remains to be made in the understanding on the exact contamination of the CMB by this component.

4. Polarisation of galactic foregrounds

Important constraints on the precision of determining the CMB polarization amplitude are imposed by galactic foregrounds which are themselves linearly polarized. Dust polarized emission provides the major contribution to the foreground polarization at frequencies of 100 GHz and above. Synchrotron emission that is intrinsically highly polarized will provide the dominant foreground up to a frequency of about 70 GHz. In between, the spinning dust could provide polarized signal as well as scattered free–free emission. Due to the uncertain predictions for the spinning dust and to the small contribution of the scattered free–free polarized emission with respect to that of the synchrotron, only the thermal dust and synchrotron polarizations are reviewed here as CMB foregrounds. Note also that studying the polarization gives strong constraints on the galactic magnetic field configuration that will not be discussed here.

4.1. Galactic synchrotron polarization

At low CMB frequencies ($\sim$100 GHz or less), the main polarized foreground is synchrotron radiation. The synchrotron radiation is intrinsically highly linearly polarised, 70–75% in a completely regular magnetic field. However, in realistic situations, several processes, such as the Faraday rotation, will reduce the polarization. The difference of rotation across the finite bandwith of the receiver will make the polarization vanish. An other depolarization occurs when the synchrotron emission arises throughout the depth of the Faraday rotating medium. In the absence of Faraday effect, depolarization occurs when polarization structures smaller than the beamwidth are present.

Polarization surveys are less extensive than intensity surveys. They cover different areas with different angular resolution with frequencies from 0.4 to 4.8 GHz. A small correlation is observed between polarization and total power, with structure in polarization seen down to 5 arcmin scale. The value for the fractional polarisation is typically 10 to 20% and can be as high as 35% (e.g., Spoelstra [17]). Strong depolarisation is observed at low frequencies.

At the CMB frequencies, the synchrotron polarization is not measured and only predictions give an estimate of its contamination to the CMB. Sky distribution of forecasted synchrotron polarization signal are dependent on the frequency spectral index and the model for the polarization angle. As a consequence of strong uncertainties on both, the simulated templates ([18–20]) have significant differences but their analysis leads to the same conclusions: the contamination from diffuse synchrotron is not a serious limitation for measuring the CMB E-mode polarization, but poses a serious challenge for measurements of the B-mode power spectrum (see Kaplan, Delabrouille and Fosalba in this issue).

4.2. Thermal dust polarization

At higher frequencies, the galactic thermal dust emission dominates, and is very poorly known in polarization (Prunet and Lazarian [21]). The alignment of interstellar dust grains by the galactic magnetic field has been known for 50 years since the early polarization observations of the stellar light in absorption (Hiltner [22], Hall [23]). This polarization is interpreted as a selective absorption of the stellar light by dust grains aligned to the magnetic field. At submillimeter and millimeter wavelengths, emission will be the dominant source of polarization, rather than the (near-IR) selective absorption. The polarized emissivity of the grains depends on their shape. The current constraints on the shape of the grains (oblate grains with an axis ratio of $(2:3)$), inferred from near-IR and optical spectro-polarimetry, predicts a polarization degree in emission of 35% for perfectly aligned grains on a uniform magnetic field in the plane of the sky. Of course, as for the synchrotron, several mechanisms will reduce the polarization. The first is the so-called 'Rayleigh reduction factor' that arises from the imperfect alignment of dust grains on the magnetic field lines. The second comes from the turbulent random component of the galactic magnetic field. The third arises from projection effects.

Due to its weakness and its wavelength domain (the submillimeter), measuring the dust polarization in emission is challenging. Observations have been first limited to few very bright molecular clouds such Orion and M17. Measured values are typically a few percent with the maximum values of 5 to 10% (Hildebrand [24]). More recently, for the first time, the balloon-borne experiment Archeops measured the dust polarization over 17% of the sky and with a 13 arcmin resolution (Benoit et al. [25] and Hamilton et al. in this issue). They find a significant galactic large scale polarized emission coherent on the longitude ranges $[100, 120]$ and $[180, 200]$ deg. with a degree of polarization at the level of 4–5%, in agreement with expectations from starlight polarization measurements. Some regions in the galactic plane show a stronger degree of polarization of about 10 to 20%. The integration along the line of sight of various orientations in the galactic Plane tends to decrease the overall effect of polarization. At high latitude, this depolarization effect should be smaller, leading to a higher polarization level. Thus, it can be anticipated that dust polarized emission will be the major foreground to CMB polarization studies with a level of about 10% of its intensity, as predicted by Prunet et al. [26]. Indeed, the signal from tensor modes of CMB is expected to be completely masked by dust.

5. Component separation

Depending on your scientific interest you will subtract the various foregrounds from the microwave measurements to recover the CMB sky, or on the contrary, you will try to recover the foregrounds from the measurements.

5.1. Subtraction methods

Subtraction methods will use an estimate of the foreground which will come from the combination of independent measurements plus some physical assumption.

For the dust one can use the extrapolation proposed by Finkbeiner et al. [27] which has been obtained in an optimal manner from the combination of the IRAS and COBE satellites data including both 5 to 40 arcmin full sky surveys from 3000 to 1250 GHz (IRAS and COBE-DIRBE), and a spectroscopic survey down to 30 GHz with 7 degree angular resolution (COBE-FIRAS). The extrapolation assumes that the dust emission follows the product of a blackbody by a power law.

The free–free estimate is obtained from full sky surveys of the H_α hydrogen emission line at 656.3 nm. This measurement in the visible range is actually heavily affected by dust extinction in the direction of the galactic plane. Some attempts have been made to correct it using the dust template of Schlegel et al. [28]. This has been done independently by Dickinson et al. [29] and Finkbeiner et al. [30]. However the result will not be valid for the narrowest part of the galactic plane where the dust opacity is too large. The frequency dependency in the microwave range will be assumed to be a power law.

For the synchrotron, one will generally use the Bonn all-sky survey at 408 MHz by Haslam et al. [1] assuming a power law for the frequency dependency. In the galactic plane one can also use higher frequency surveys at 1400 MHz in order to adjust the slope of the power law in each sky direction.

5.2. Separation methods

We would of course prefer separation methods because we do not think that the knowledge of the foregrounds is good enough to avoid finding it from the microwave data itself. In other words, we are convinced that there is much to be learnt, and probably not always as expected (see the question of the anomalous emission above), from the microwave measurements of the galactic emissions.

A separation method will generally be based on a chi-square fit of some parametrised spectral model of the different components to the multiband measurements. For instance for the dust we will adjust the temperature and the spectral index, and we will fit a spectral index for each of the free–free and the synchrotron. However, in order to regularise the solution and avoid unphysical negative components, it is better to add to the chi-square likelihood an entropy term which will force each component to be positive and eventually approach a peculiar template. The total likelihood can then be written:

$$L = \exp\left(-\frac{\chi^2}{2}\right) + \lambda \sum \left[I \log(I/T)\right], \tag{1}$$

where I stands for the recovered component, T for its template, and the sum is over all components. This method has been used on a pixel basis for the WMAP data analysis using the templates described in the previous section (see Bennett et al. [2]). The good point of the method is that the components restored depend very little on the template used. One can get convinced of this by looking at the striking differences between the synchrotron template (Fig. 1) and the recovered WMAP synchrotron (Fig. 3).

6. Conclusions

The microwave frequencies open a unique window on the Universe in general, and on our Milky-Way in particular. This is firstly because this electromagnetic window is almost fully transparent down to the recombination era, giving us a unique opportunity to see through the galactic plane. In addition, almost all components of the diffuse matter in space shine in this frequency range: dust, ionised gas, and energetic particles for broad band continuum emissions; but also molecular and HI line transitions. This diffuse matter, which is continuously accreted from extragalactic space, makes our Milky-Way a very productive star factory. The detailed observation of this process in our Galaxy is potentially able to bring us clues to understand the star formation process in the very early universe.

It is clear that the current understanding of the diffuse matter in space and of its emissions are not yet complete. The so called *anomalous microwave emission* shows us one aspect. It is likely that more detailed measurements of the sensitive new generation CMB missions to come (PLANCK and after) will bring us more unexpected results. Those might be a nightmare for the cosmologist but certainly a delight for those who are interested in our Galaxy.

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