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2002-TR-16

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Abstract

The DMR-COBE maps (available of the public COBE database on WWW) of the cosmic CMB radiation and of the major microwave Galactic components have been studied. The existence of significant correlations among the Galactic sources is experimentally observed, together with a relationship between these correlations and the Galactic coordinates. Specifically, an important dependence on the longitude is found for the correlation coefficients: these are the highest near ±30° Galactic longitude and they decrease being almost null in the outer Galaxy around (180, 210)°. Moreover an anti-correlation between the free-free and the CMB emission is found for Galactic latitude > |30°|. These findings are discussed in terms of the expected relationship among the astrophysical sources and of the possible effects related to source-separation techniques.

Categories and Subject descriptors: *(ACM) – J.2 Computer Applications [Physical Science and Engineering: Astronomy]; I.4.0 & I.4.5 Image Processing and Computer Vision [General: Image Processing Software, Reconstruction]; (MSC) – 85A40 Cosmology.*

1. Introduction

The possibility of making accurate measurements of the Cosmic Microwave Background (CMB) radiation is fundamental for imposing tight constrains on cosmological parameters that may allow to distinguishing among competitive theories of structure formation in the early Universe (Sachs and Wolfe, 1967). Measurements of microwave sky maps represent the overlapping of Galactic emissions on the possible cosmic signal, thus the separation of background and foreground radiations is crucial in CMB investigations.

After many attempts to distinguish between Galactic and potential cosmic emissions (e.g., Fixsen et al., 1983; Lubin et al., 1985; Boughn et al., 1990), a successful separation was achieved for data from the Cosmic Background Explorer (COBE), which allowed the observation of CMB temperature fluctuations at an angular resolution of 7° FWHM, interpreted as Sachs-Wolfe anisotropies (Smoot et al., 1992; Gorski et al., 1996). In particular, accurate techniques were used for the separation of COBE-DMR (Differential Microwave Radiometers) sky maps into their major Galactic and extragalactic components, based on astrophysical models and measurements of Galactic emissions available before COBE and on observations at multiple DMR channels centred at 31 GHz, 53 GHz and 90 GHz (e.g., Bennet et al., 1992).

In order to improve the microwave CMB observations, new experiments are planned. In particular, for the Planck mission, the Low Frequency Instrument (LFI) is going to give sky maps at frequency ranges (30 GHz to 100 GHz) in part coincident with the COBE-DMR ones. In addition, LFI is aimed to reach higher angular resolution (30' ÷ 5') and higher sensitivity (few μK) (Mandolesi et al., 2000; Lamarre et al., 2000).

In this context, the implementation of new algorithms is in course of study to allow an efficient and automatic all-sky astrophysical component separation (Baccigalupi et al., 2000; Maino et al., 2001, Kuruoglu et al., 2002). In the Blind Source Separation (BSS) field, several methods can be used, based on the a-priori knowledge about the sources. One important difference among these methods is the dependence or independence of the overlapping signals, designating the two categories: Independent Component Analysis, ICA (e.g., Baccigalupi et al., 2000) and Dependent Component Analysis, DCA (e.g., Nuzillard and Nuzillard, 1999).

This paper is intended to study the dependence or independence among the COBE-DMR astrophysical sources in order to derive the preliminary information necessary to specialize an optimal ICA or DCA algorithm for the Planck-LFI observations.

	Synchrotron	Free-Free	Dust
CMB	-0.196	-0.579	-0.188
Dust	0.900	0.850	
Free-Free	0.762		

Table I. *Correlation coefficients among the map of the CMB and the maps of the Galactic emissions; the number of pixel points considered in each correlation is 6144 corresponding to the whole sky.*

2. Data Analysis and Experimental Observations

The data considered here are the Analysed Science Data Sets (ASDS) from the DMR on board of COBE, which provides the best available low-frequency (< 100Ghz) all-sky maps, before the expected first release of Microwave Anisotropy Probe, expected by January 2003. In particular these data have been downloaded from the public COBE site at the WWW address http://space.gsfc.nasa.gov/astro/cobe/cobe_home.html.

For details about the DMR we address to papers by Smoot et al. (1990) and Bennet et al. (1992).

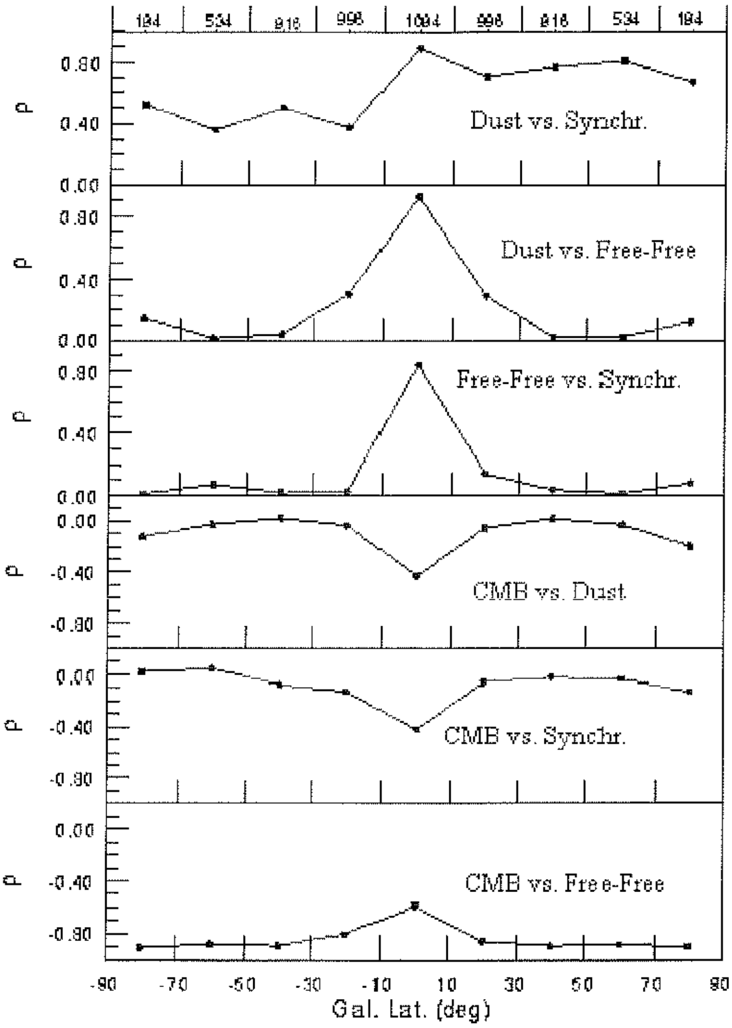

Figure 1. *Correlation coefficient, ρ, between the emissions indicated in each panel and calculated for separate Galactic latitudes (each ρ is shown at the centre of the latitude range to which it refers); the numbers at the top of the figure indicate the number of data points in each latitude range.*

In particular the ASDS data consist of Galactic and cosmic emission maps, after removing of the first order dipole anisotropy. These maps are obtained by processing 4-year data sets and represent all the sky for each one of the sources giving important contributions at microwave wavelengths: (a) CMB component, (b) synchrotron emission, (c) free-free emission and (d) thermal emission from the dust. The separation of these four components has been calculated by using two techniques: the *subtraction* and the *combination* techniques. For details about these techniques we refer to papers by Bennet et al. (1992a; 1994) and to the following Discussion paragraph.

The correlation coefficients among the corresponding pixels of the four COBE maps of astrophysical source emissions have been calculated for all the sky and results are reported in Table I. The most significant correlations are found between the dust and synchrotron emissions and between the dust and the free-free ones. The correlation coefficient between the free-free and the synchrotron emissions is found to be ~ |0.1| smaller. The most uncorrelated source is the CMB, which presents only a relatively weak (but still statistically significant at a confident level above 99.9%) anti-correlation coefficient with the free-free emission.

In order to study the possible association between the level of the correlations and the Galactic coordinates, we have calculated the same correlation coefficients reported in Table I, but for separate ranges of Galactic latitude and longitude. Results are reported in Figure 1 and 2 for intervals of 20° Galactic latitude and 30° Galactic longitude respectively.

Figure 1 shows a very good anti-correlation between the CMB and the free-free emissions at latitudes north/south of ±30°. Moreover a relatively good correlation is shown in the top panel between the dust and the synchrotron sources, being higher in the northern than in southern Galactic hemisphere. The rest of the correlations are generally quite close to zero except in the latitude range (-10, 10)°, where, in particular, coefficients as high as an order of 0.9 are achieved among the synchrotron, the free-free, and the thermal dust emission.

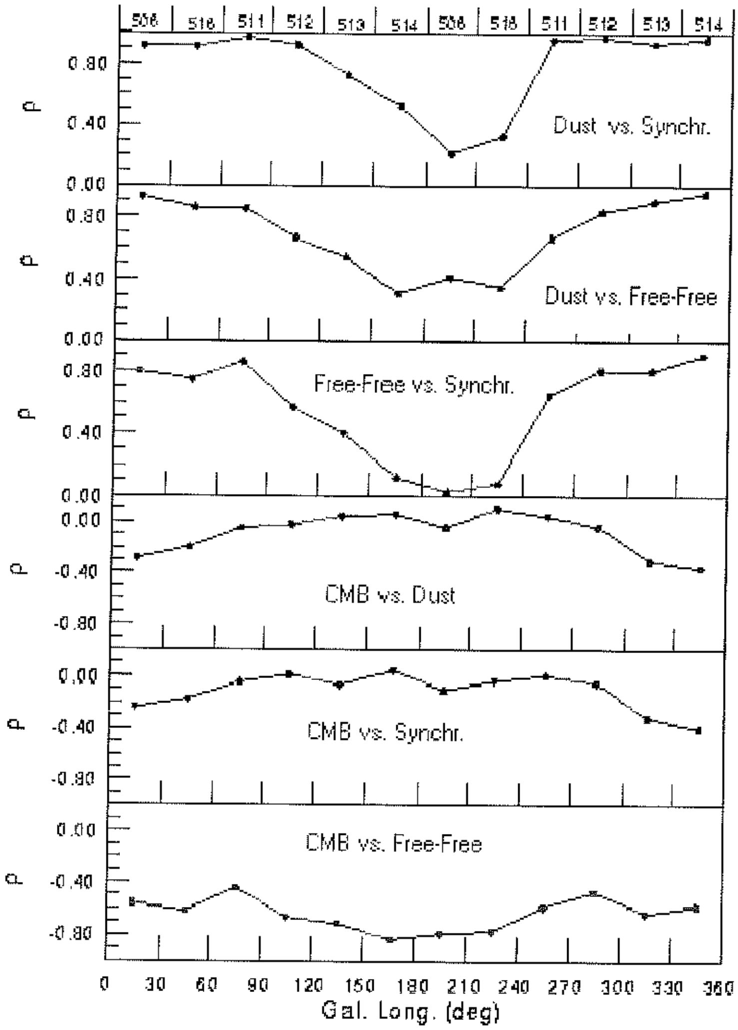

Figure 2. *Correlation coefficient, ρ, between the emissions indicated in each panel and calculated for separate Galactic longitudes (each ρ is shown at the centre of the longitude range to which it refers); the numbers at the top of the figure indicate the number of data points in each longitude range.*

In Figure 2 the Galactic longitude modulations are reported for the correlations among the considered sources. The top panel shows that the correlation coefficient between the thermal dust and the synchrotron emission is equal or higher than 0.9 at Galactic longitudes <120° or >240°. In particular, the longitude is a key parameter affecting the relationship between these emissions. In fact if we re-calculate the correlation coefficient considering together all pixels for Galactic longitude < 120° and > 240°, the scatter is much higher. This is due to the fact that the best fit is changing with the longitude, as Figure 3 illustrates: the top panel of Figure 3 is referring to Galactic longitude (240, 270)° and shows that the best fit has an angular coefficient equal to 1.69, while the bottom panel is referring to Galactic longitude (60, 90)° and shows a best-fit angular coefficient equal to 0.89. At the same time it is worth to note that the two correlations shown in Figure 3 are both similarly significant, independent of the different variability of the involved parameters (smaller in the top panel than in the bottom one).

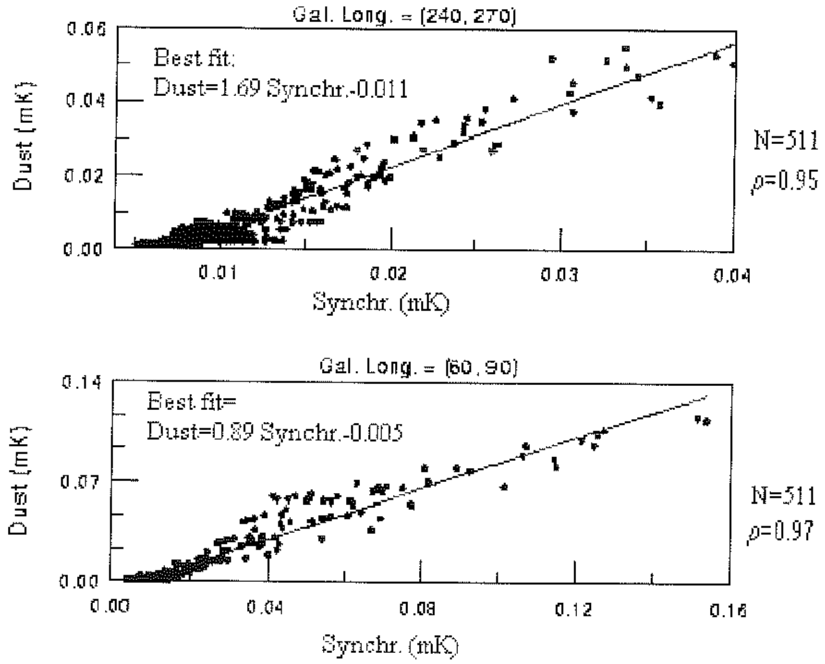

Figure 3. *Example of the difference between two best fits related to two separate Galactic latitude intervals for the thermal dust vs. synchrotron emission; the number of data points (N) and the correlation coefficient (ρ) are indicated on the right.*

In order to investigate if the dust-synchrotron correlation for Galactic longitude (120, 240)° is better with restriction of the latitude range around zero (see Figure 1), we have shown in Figure 4 the scatter plots and best fits for longitude (180, 210)° with and without restriction of the latitude in the range (-10, 10)°. It is found that, at this longitude, the correlation is definitely lower than elsewhere also near the Galactic equator. Out of the Galactic equator, the lack of correlation is clearly related to the large scatter of thermal dust emission occurrence for synchrotron sources around 0.015 mK. A similarly larger scatter for the dust emission is found for synchrotron radiation around 0.015 mK for the other longitude intervals around (180, 210) °. This effect suggests contamination of the dust signal by a different thermal emission in the outer Galaxy region further from the Galactic plane.

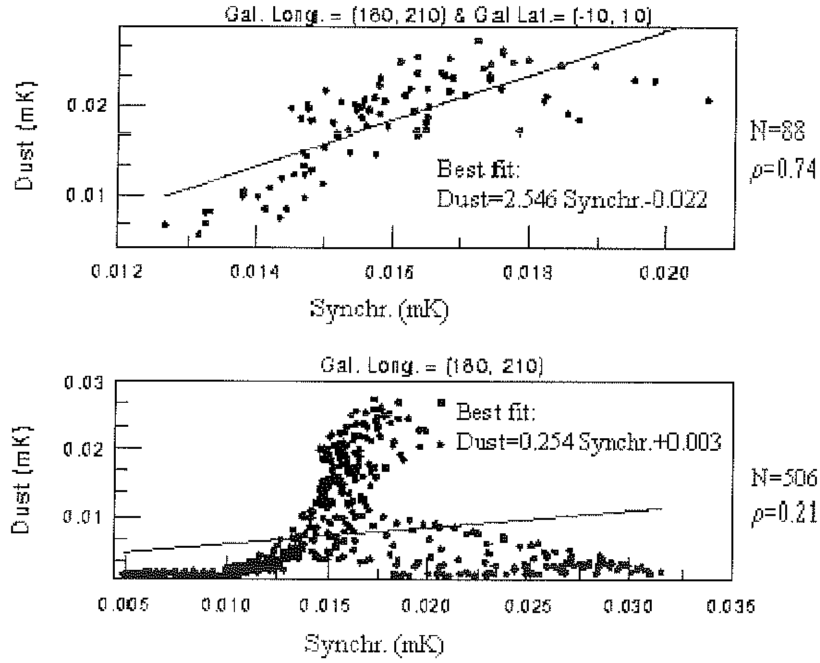

Figure 4. *Correlations between dust and synchrotron at Galactic longitude (180, 210) ° with all latitude pixels (bottom panel) or exclusion of pixels out of (-10, 10)° Galactic latitude interval (top panel)*; the number of data points (N) and the correlation coefficient (ρ) are indicated on the right.

The importance of the Galactic longitude in affecting the relationships dust vs. free-free and free-free vs. synchrotron emissions is evident in the second and third panels from the top of Figure 2: these correlations are minimum around (180, 210)° longitude, similarly to the dust vs. synchrotron correlation. Also for the cases dust vs. free-free and free-free vs. synchrotron, the best fits are different in separate ranges of longitude, similarly to results shown in Figure 3.

Differently, the best fit for the CMB vs. free-free emissions (bottom panels in Figure 1 and 2) is not significantly dependent on the latitude or on the longitude. In fact, if we calculate it in separate latitude interval we obtain similar angular coefficient and intercept. Thus, grouping together all data in the latitude interval (-90, -30)° and (30, 90)° (see Figure 5), the anti-correlation coefficient is close to -0.9. Therefore, for the CMB vs. free-free emissions a general best fit can be established that has an angular coefficient ~ –0.7 and an intercept ~ -0.02.

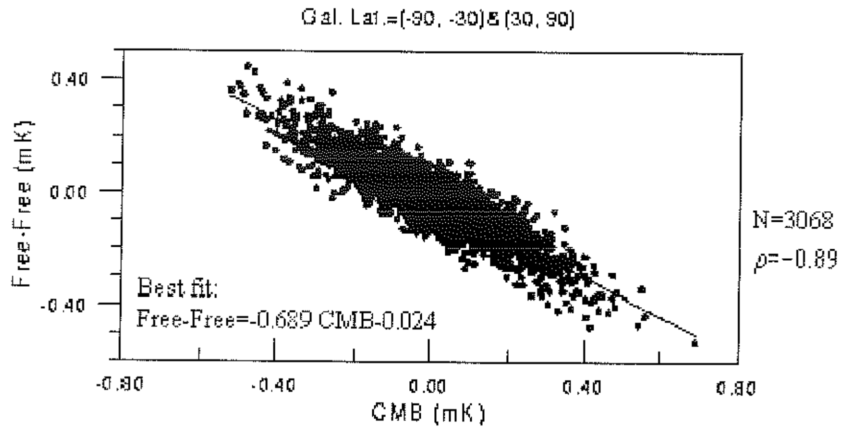

Figure 5. *Correlation free-free vs. CMB for pixels with Galactic latitude in the ranges (-90, -30)° and (30, 90)°; the number of data points (N) and the correlation coefficient (ρ) are indicated on the right.*

Moreover, Figure 2 shows low correlation coefficients for the CMB vs. dust and CMB vs. synchrotron emissions, with just a slight increase at longitudes around zero.

In order to verify how the different variability of the parameters is affecting the findings above, we have illustrated in Figure 6 and Figure 7 the average, the maximum and minimum values for the four emissions in each considered interval of latitude and longitude.

In particular Figure 6 shows an increase of free-free variability near the Galactic equator and rather constant latitudinal variability for the CMB. Thus an increase of CMB vs. free-free anti-correlation coefficient in the range (-10, 10)° latitude should be expected. This increase is not observed in Figure 1, implying independence of related results on parameter variability.

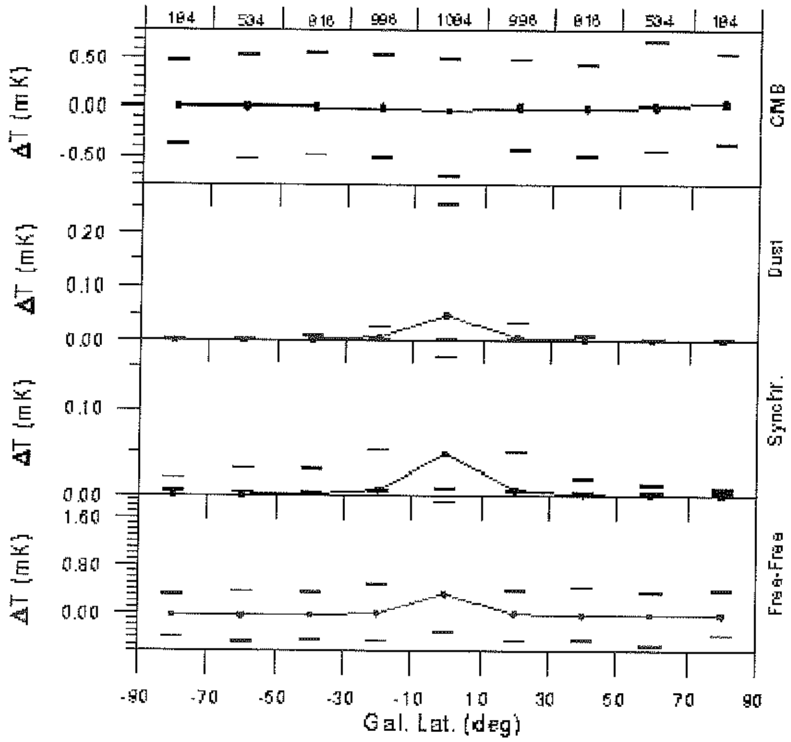

Figure 6. *The dot points are the averages at separate latitudinal ranges (each point is illustrated at the centre of the 20° Galactic latitude interval to which it refers) of CMB, thermal dust, synchrotron and free-free emissions (respectively from the top to the bottom panel); the horizontal bars indicate the maximum and minimum value for each sub-set; the numbers at the top indicate the number of pixels considered in each average.*

Similarly, the comparison between Figure 2 and 7 indicates that our considerations about dust vs. synchrotron correlation are not dependent on the parameter variability, as already shown in Figure 3 and Figure 4.

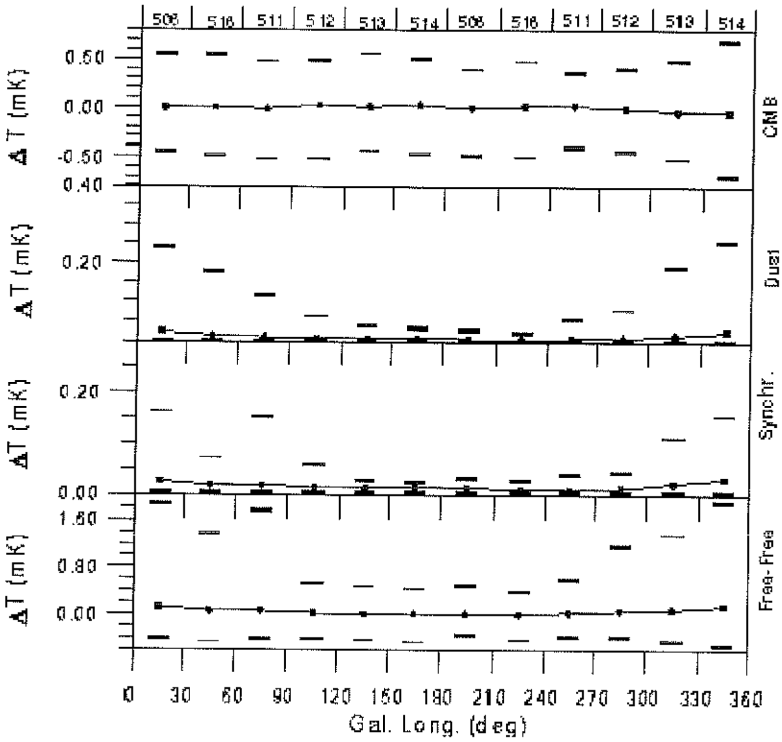

***Figure** 7. The dot points are the averages at separate longitudinal ranges (each point is illustrated at the centre of the 30° Galactic longitude interval to which it refers) of CMB, thermal dust, synchrotron and free-free emissions (respectively from the top to the bottom panel); the horizontal bars indicate the maximum and minimum value for each sub-set; the numbers at the top indicate the number of pixels considered in each average.*

Differently, the increase of the correlations in the second to fifth panels of Figure 1, near the Galactic equator, can be interpreted in terms of the larger variability of the parameters involved (see Figure 6). Finally, also the longitudinal dependence of free-free vs. dust and free-free vs. synchrotron correlations (see Figure 2) can be related to the parameter variability shown in Figure 7. This is further detailed in Figure 8 for the free-free vs. synchrotron (the free-free vs. dust case is similar), where the top panel has lower correlation coefficient and lower range of values for the two considered emissions.

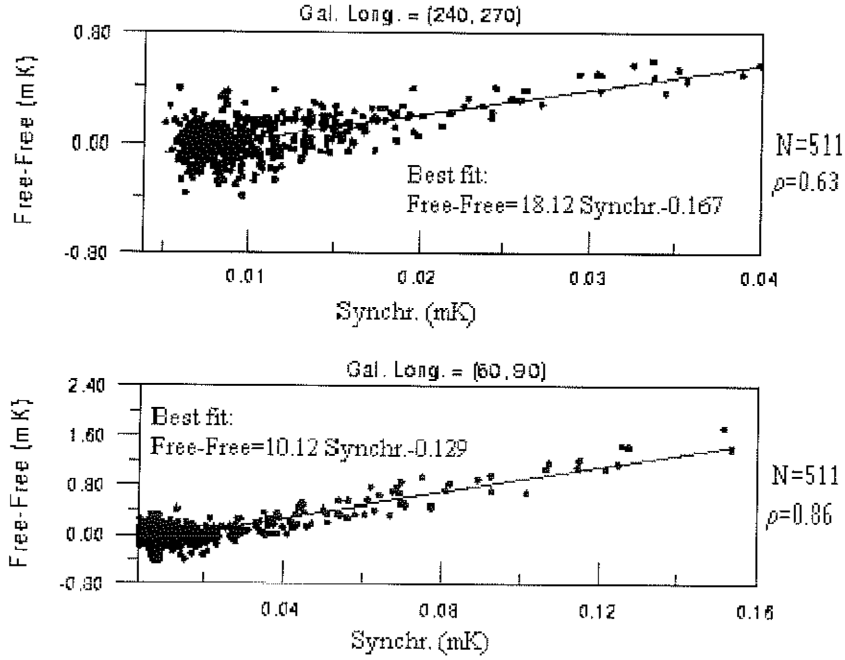

Figure 8. *Correlation free-free vs. synchrotron for pixel with Galactic longitude in the range (240, 270)° (top panel) and (60, 90)° (bottom panel); the number of data points (N) and the correlation coefficient (ρ) are indicated on the right.*

3. Discussion

Possible correlations among Galactic emissions can be expected, based on the functions expressing the intensity of the considered radiations. Specifically a correlation can be expected between the synchrotron and the free-free emissions, in fact: (a) the synchrotron intensity is proportional to $Ne(E, l)\, dE\, dl$, with $Ne(E, l)$ equal to the number of relativistic electrons at energy E per unit of volume along the line of sight l (e.g., Pacholczyk, 1970); (b) the free-free intensity is proportional to $Ne(l)Ni(l)\ dl$, with $Ne(l)$ and $Ni(l)$ equal, respectively, to the number of electrons and ions per unit of volume along the line of sight l (often it is approximated $Ne(l)=Ni(l)$, thus the free-free emission is considered proportional to $Ne^2(l)\ dl$) (Oster, 1961). Moreover, the radiation from the dust (denser where the line of sight samples denser dust) is the thermal emission from interstellar dust grains; thus, in two line of sights of hypothetically equal dust distribution, this emission is expected to be higher in regions of local higher temperature or energy (which are parameters in common with the free-free and the synchrotron mechanisms).

Nevertheless, differences among the considered microwave Galactic sources are also expected. Firstly, this is true for what is related to their frequency dependence: an increase of dust emission with increase of frequency is in agreement with its black-body/grey-body nature, while a decrease of synchrotron and free-free emissions with increasing frequency is well theorized (references above). In addition, different spatial variations are expected due to local characteristics of the Galaxy at different lines of sights. E.g., a spatially variable spectral index is theorized for the synchrotron radiation, together with its proportionality to the *effective* magnetic field strength (Reich and Reich, 1986; Bennet et al., 1992a; and references therein). Thus, in a region of small or absent magnetic field, the significant decrease of the synchrotron emission is not necessarily associated with a similar decrease of the free-free radiation (dependent on kinetic energy or temperature of involved electrons and ions, but unrelated to the local magnetic field), while it may be still associated with a relative decrease of the thermal emission from the dust.

Previous observations are in agreement with the finding that the correlation coefficient of the synchrotron with the dust emission is more significant than the one with the free-free component (shown in Table I).

Regarding the CMB correlations, it is expected that the CMB (that is a cosmic signal) is uncorrelated to the Galactic dust and synchrotron components, in agreement with our findings. Differently, it is not evident any specific reason for the significant correlation that we found between the CMB and the free-free emissions. A possible interpretation might be related to the techniques used for deriving the galactic and cosmic microwave emissions.

The several COBE-DMR techniques used for the separation of the astrophysical sources are rather equivalent one another and they are based on the assumption that the frequency dependences of all sources are known and independent of the coordinates (Bennet et al., 1992a). In particular one technique is the *subtraction technique*, which consists of: (a) subtracting the synchrotron and dust models (derived by using data at frequencies where these emissions are dominant) from the sky map at 31.5 GHz; (b) scaling the resulting 31.5 GHz map to 53 GHz and 90 GHz with the assumed frequency dependence for the free-free emission; (c) subtracting the maps obtained at 53 GHz and 90 GHz at point *b* from the ones at the corresponding frequency at point *a*; (d) restoring the maps obtained at point *c* correcting back for the CMB frequency dependences in order to derive the cosmic map only; (e) averaging the three cosmic maps obtained at the three frequencies as the final cosmic map; (f) subtracting this average cosmic map from the map at 31.5 GHz resulting from point *a* gives the free-free map.

By comparing our results with details of the *separation technique* above, some coincident associations are found. The first one is related to the correlation coefficient between the synchrotron and the dust emission that is more significant in the northern than in the southern hemisphere (shown in Figure 1). This can be associated with the fact that the synchrotron model (and in particular the associated *effective* Galactic magnetic field), used at point (a) of the *subtraction technique*, is derived from measurements at 408 MHz and at 1420 MHz, which are not available for $\delta < -19$. So in that region the effective Galactic magnetic field was assumed to be 1.4 μG, which is actually the median of the magnetic field all over the rest of the surveyed sky, but rather significantly different of specific local values varying from 0.1 to 5 μG (Bennet et al., 1992).

Moreover, after subtraction of dust and synchrotron, the resulting map is considered to be the sum of free-free and CMB components (as specified above). Thus, where the free-free is assumed to be a higher percentage of the observed differential temperature, the CMB is a smaller one and vice-versa. This might affect the results illustrated in Figure 5 and in particular the best-fit obtained which shows the anti-correlation CMB vs. free-free emission. Further, the fact that the considered free-free emission model (because of its known association with the H_α emission) is modulated as $csc\ |b|$ for $|b| > 15°$ (where b is the Galactic latitude) might force the latitudinal dependence of CMB. This is so unless the measured total sky already contains the $csc|b|$ dependence initially, which should not be true.

Comparing the observations above with the findings in Figure 1, we note that the absolute value of the free-free vs. CMB correlation coefficient is smaller just for $|b|<10°$, where the $csc|b|$ rule cannot apply. This might suggest that this is a region where a better CMB-free-free separation is achieved.

One surprising result illustrated in Figure 2 is related to the decrease of correlations among the three Galactic components for longitude >|120°|. This is particularly interesting if we consider that this correlation decrease is driven by data at latitude >|10°|, off the Galactic plane and it is related to the appearance of large levels of dust emission at synchrotron temperatures around 0.015-0.020 mK. A detailed identification of this spurious emission is in course of study and makes use of data at other frequency range.

Presently, it is worth to note possible associations between outer Galaxy results and the assumptions made by the *combination technique*. For this technique, the cosmic map is obtained by combining the DMR multi-frequency antenna temperature maps $T_{Cosmic} = W_{31} T_{31} + W_{54} T_{54} + W_{90} T_{90}$. In particular the three weights W are derived by considering a system of three equations corresponding to (Bennet et al., 1992a): (1) the final map is normalized in units of Planck brightness temperature ($W_{31} / 1.026 + W_{54} / 1.074 + W_{90} / 1.226 = 1$), (2) the free-free contribution to the final map is set equal to zero ($W_{31} R_{f31} + W_{54} R_{f54} + W_{90} R_{f90} = 0$, where R takes into account the frequency dependence factor for the free-free emission), (3) the average signal in the outer Galactic plane, $\sin|b| < 0.1$ & $|l| > 30°$, is set equal to zero. This latter condition is making use of the average antenna temperatures at the frequencies 31.5, 53 and 90 GHz all over the region $\sin|b| < 0.1$ & $|l| > 30°$. Possibly, important differences for these temperatures occur for the outer latitudes, which explain observations in Figure 2. More importantly, this is based on the assumption that the cosmic emission in the outer galactic plane is small, which (although relatively true) may lead the conditioning of the obtained maps of CMB and Galactic emissions.

Although all previous observations, it is well known that the COBE separation techniques were certainly sufficiently precise for indicating the presence of important CMB component for the observed anisotropy, which cannot be explained by anisotropies of the Galactic signals (e.g., Smoot et al., 1992). In addition, the formulation of models always implies the establishment of a certain degree of approximation related to the fact that not all the component sources are entirely known all over any region of the whole sky.

In this context, the present study indicates the importance of BSS methods and the necessity of taking into account the presence of correlations among considered sources, with eventual differentiation for separate longitude intervals. Specifically, the use of DCA algorithms is more convenient than the ICA ones (Baccigalupi et al., 2000), which can be seen only as specific cases of the more generic DCA (e.g., Barros, 2000).

4. Conclusions

The possibility of finding significant correlations among Galactic microwave sources is studied for the COBE-DMR data. In particular, statistically significant correlations are found among all the three important sources of microwave Galactic radiations: free-free, synchrotron and thermal dust emissions, being the best correlation coefficients found for the dust vs. synchrotron and dust vs. free-free components. These correlations are interpreted in terms of their common dependence on the local electron density and on the local temperature or energy level along the specific lines of sight.

The relationship between these correlations and the Galactic coordinates of the lines of sight is investigated. Results show that the dust vs. synchrotron correlation coefficients are > 0.9 for Galactic longitude in ranges $(0, 120)°$ & $(240, 360)°$. Moreover, at these locations, the best fits are changing as a function of the longitude. Similar longitudinal dependence is found for the correlations of dust vs. free-free and synchrotron vs. free-free emissions, with small or null significance around Galactic longitude (180, 210)°. This effect is discussed in association with the approximations used for modelling emissions in the outer Galactic regions.

A rather significant anti-correlation is found between the CMB and the free-free emissions and it is specifically related to Galactic locations with latitudes > |30|. The interpretation of this result is rather doubtful, suggesting a direct relationship with the COBE-DMR separation techniques.

The usefulness of taking into account the possible correlations among Galactic sources is discussed, addressing to BSS methods efficient also in case of non-orthogonal signals.

5. Acknowledgements

The COBE-DMR data are provided by the US Government Public Information Exchange Resource operated by the Astrophysics Data Facility, Code 631, NASA/GSFC Greenbelt, MD 20771, USA.

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