We review present understanding of Galactic free–free emission and its possible importance to CMB fluctuation measurements. Current results, from both “direct” observations in the microwave band and from \( \alpha \) studies, suggest that this foreground does not represent a serious obstacle to mapping the CMB; however, this is based on limited information and we emphasize the need for more exhaustive studies. We also present some preliminary results based on our recent \( \alpha \) observations near the South Pole CMB data sets. The fluctuation amplitude seen in \( \alpha \) indicates that the detected CMB fluctuations are not significantly contaminated by free–free emission, at least if the diffuse gas is at a temperature of \( T \sim 10^4 \) K.

1 Galactic Free–free Emission

The three main sources of microwave emission from our Galaxy are synchrotron radiation, thermal dust emission and bremsstrahlung (free-free emission). Among these three, bremsstrahlung poses the greatest difficulty for cosmic microwave background (CMB) observations for two reasons: 1/ it dominates over the frequency range where the total Galactic emission is minimal, and hence where the majority of CMB experiments are performed, and 2/ it dominates only over a small range of frequencies (see Fig. 3 of Kogut et al. 1996a). Thus, it is the principal Galactic contaminant of many CMB experiments, but it cannot be traced by observing at either much
higher or lower frequencies. For example, the dust and synchrotron foregrounds may be mapped in the infrared and radio, respectively. Such maps prove very useful for foreground control and elimination. There exists, nevertheless, a tracer of Galactic bremsstrahlung – Hydrogen Hα in emission, which is produced by the same warm ionized medium (WIM) responsible for the bremsstrahlung. Unfortunately, there is at present no full-sky map available in Hα. In what follows, we review what is known about Galactic free-free emission, with an emphasis on implications for CMB experiments. We will first consider “direct” observations of the foreground in the microwave band (from CMB work) and then consider in detail studies based on the Hα line. An excellent recent review of the subject has been given by Smoot (1998). To focus the discussion, we will center it on two primary questions: 1/ How well correlated are dust and free-free emissions? 2/ Might there be a hot component of the interstellar medium (ISM) producing Galactic free-free emission which could violate limits based on a simple interpretation of current Hα observations?

1.1 Direct Observations of Bremsstrahlung

A summary of direct observations of Galactic bremsstrahlung in terms of equivalent brightness temperature variations at 40 GHz (Q-band) – ∆T_{ff} – is given in Table 1. All these results come from CMB experiments. The three DMR maps, obtained at 31.5, 53 and 90 GHz, have been combined to optimize a signal with the spectral dependence of free-free emission, ∼ ν⁻² (Kogut et al. 1996a, 1996b) (this has been done for all three Galactic emissions; the maps are available at [http://nssdc.gsfc.nasa.gov/astro/cobe/cobe_home.html](http://nssdc.gsfc.nasa.gov/astro/cobe/cobe_home.html)). Unfortunately, the signal-to-noise in the resulting free-free map is too low to follow in detail the distribution of Galactic bremsstrahlung. Nevertheless, based on the COBE 4 year results, Kogut et al. (1996b) constrain the brightness fluctuations due to bremsstrahlung to ∆T_{ff} = 9±7μK. This provides a 95% upper limit of ∆T_{ff} < 23μK on the total Galactic free-free emission. For comparison, the extracted CMB fluctuation amplitude (brightness variations at 10°) is 29 ± 1μK (Banday et al. 1997).

In order to boost the signal-to-noise, Kogut et al. (1996b) also searched for galactic emission by cross-correlating the three DMR and the DIRBE 140 micron maps, finding a significant result. The spectral characteristics of the correlated signal are those of a combination of dust and free-free emission, with the free-free contributing ∆T_{ff} = 12±5μK. Within the errors, this is consistent with the above upper limit, but it does leave room for a non-correlated component of the same amplitude.
Table 1: Summary of Direct Free–Free Constraints

| reference                          | resolution | patch size         | $\Delta T_{ff}$ at 40 GHz | comments                   |
|------------------------------------|------------|--------------------|----------------------------|----------------------------|
| Kogut et al. 1996b: (DMR/DIRBE)    | $10^\circ$ | $|b| > 20^\circ$   | $12 \pm 5 \mu K$           | dust correlated total emission |
| (DMR)                              |            |                    | $9 \pm 7 \mu K$            |                            |
| de Oliveira–Costa et al. 1997 (Saskatoon) | $1^\circ$  | $7.5^\circ \times 7.5^\circ$ | $17.5 \pm 9.5 \mu K$       | dust correlated no spectral info. |
| Leitch et al. 1997 (OVRO 5.5 & 40 m) | $0.3^\circ$ | DEC = $88^\circ$  | $\sim 27 \mu K$           | total emission              |

Oliveira–Costa et al. (1997) performed a similar analysis on the Saskatoon data, cross–correlating the CMB results with the DIRBE far infrared maps. They marginally detect a non–zero correlation with an amplitude consistent with that found by Kogut et al. (1996b), extending the free–free/dust correlation down to angular scales of $\sim 1^\circ$ (the COBE results are restricted to $>7^\circ$). These results raise the first question posed in the introduction: Just how well does dust emission trace Galactic bremsstrahlung? The COBE and Saskatoon analyses demonstrate the existence of a free–free component correlated with Galactic dust emission, but it should be remembered that the possibility of an equally important, non–correlated component remains. The angular power spectrum of the dust–correlated component is $P(l) \sim l^{-3}$ (Kogut et al. 1996b), showing a rapid fall–off towards small angular scales. This power spectrum is not at all surprising – it is simply the power spectrum already observed for the dust distribution (Gautier et al. 1992; Wright 1998). It is worth noting that such a power spectrum implies that the true sky variance remains roughly constant towards small scales, but that estimates of this variance in restricted patches of sky may be “pulled” far from the true variance by the important correlations on scales equal to the patch size; in other words, the uncertainty on the estimate will be larger than that deduced by assuming $N_{\text{pixel}}$ independent measurements of the sky brightness. This should be kept in mind when interpreting the estimates given in the tables.

Complicating matters somewhat is a recent result reported by Leitch et al. (1997). Using the OVRO 5.5 and 40 meter telescopes at frequencies of 32 and 14.5 GHz, they find a large signal in a ring at constant declination around the North Celestial Pole (Saskatoon region) with the spectral characteristics of free–free emission. The corresponding 40 GHz amplitude on an angular scale of $0.3^\circ$ is $\Delta T_{ff} \sim 27 \mu K$, slightly larger than the upper limits imposed on larger scales by the previous observations or by the extrapolation of the dust power spectrum. This result could indicate the emergence on smaller scales of an important bremsstrahlung component uncorrelated with dust. We return to this point below when discussing the H$\alpha$ results.

1.2 H$\alpha$ Studies

The ionized gas responsible for the free–free emission is also a source of line emission, in particular Hydrogen H$\alpha$. This optical line, at 6563 angstroms, may thus be used to trace the gas distribution and, hence, map the free–free foreground (Ly$\alpha$ would do the same, but absorption
is a serious problem). In the following, we present simplified versions of the various formulae; a more detailed treatment can be found in Valls–Gabaud (1998). The Hα intensity, usually expressed in terms of Rayleighs \( R = 2.41 \times 10^{-7} \text{ergs/cm}^2/\text{s/ster} \), is given by

\[
I_\alpha = (0.36 \, R) \left( \frac{EM}{\text{cm}^{-6} \text{pc}} \right) T_4^{-0.9}
\]

where \( T_4 \equiv T/(10^4 \, \text{K}) \) and \( EM \) represents the emission measure. This expression is valid for temperatures \( T_4 \leq 2.6 \) (Leitch et al. 1997). Free–free emission depends on the same quantities (given here for pure Hydrogen and in the limit as \( h\nu/kT \to 0 \)):

\[
T_{ff} = \frac{(5.43 \, \mu\text{K})}{\nu_10^2 T_4^{1/2}} \left( \frac{EM}{\text{cm}^{-6} \text{pc}} \right) g_{ff}
\]

where the observation frequency is \( \nu = \nu_10 \times 10^{10} \, \text{GHz} \) and \( g_{ff} \) is the thermally averaged gaunt factor:

\[
g_{ff} = 4.69(1 + 0.176 \ln T_4 - 0.118 \ln \nu_10)
\]

The relation between the line and free–free emissions is particularly simple due to the fact that both depend primarily on the emission measure. Combining Eqs. (1) and (2) yields

\[
T_{ff} = (15 \, \mu\text{K}) g_{ff} T_4^{0.4} \nu_10^{-2} \left( \frac{I_\alpha}{R} \right)
\]

Table 2: Hα Results

| reference            | resolution | patch size         | \( \Delta T_{ff} \) at 40 GHz | comments         |
|----------------------|------------|--------------------|--------------------------------|------------------|
| Reynolds et al. 1990 | 0°.8       | diverse pointings  | \~10 \mu K                     | Fabry–Perot      |
| Reynolds et al. 1992 | 0°.8       | 12° × 10°          | \~10 \mu K                     | Fabry–Perot      |
| Gaustad et al. 1996  | 0°.1 – 1°  | 7° × 7°            | <5 \mu K                       | broad–band       |
| Simonetti et al. 1996| 1°         | diam = 30°        | <5 \mu K                       | broad–band       |
| Marcelin et al. 1998 | 0°.5       | 24 pointings       | <5 \mu K                       | Fabry–Perot      |

The ideal would therefore be to have a sensitive all–sky map in Hα to control the free–free foreground; this does not at present exist. For many years, R. Reynolds has been carrying out Hα observations of the Galaxy with a double Fabry–Perot spectrometer (needed to separate Galactic Hα from the much larger geocoronal Hα emission). A good review of these results and a summary of what is known about the distribution of the WIM is given by Reynolds (1990). For the essential, the gas seems to be distributed above and below the Galactic Plane with a characteristic scale height of \~1 \text{kpc}. It is thought that the gas has a temperature close to \( T_4 = 1 \). These conclusions are the result of diverse, pointed observations (a rough
picture of the gas distribution is given in Reynolds 1990). A significant improvement will soon come from the WhaM survey (Reynolds et al. 1998), an effort to map the northern sky in Hα at a resolution of 1° (the WhaM web page is a very useful source of information – [http://www.astro.wisc.edu/wham/WhaM.html](http://www.astro.wisc.edu/wham/WhaM.html)).

A rough summary of current results from Hα is given in Table 2, where we have assumed $T_4 = 1$. We note that the small-scale observations are essentially upper limits, but that Reynolds actually sees fluctuations at $\sim 2$ R. From this compilation, it would seem that the variations on small scales are not very large and should not pose a problem for CMB experiments, which are expecting signals in the range $30 - 100 \mu K$. An important caveat is always that, up till now, these observations cover a rather small fraction of sky. The last entry, Marcelin et al. (1998), is discussed below.

The Gaustad et al. (1996) and Simonetti et al. (1996) observations cover the Saskatoon area (North Celestial Pole). They are based narrow band filters instead of the high resolution spectrographs used by Reynolds et al. and Marcelin et al. This means that they are unable to extract the geocoronal from the Galactic signal, implying that only upper limits on Hα fluctuations can be deduced. Their strict limits argue against a significant level of contamination in the CMB results from Saskatoon. However, as already mentioned, Leitch et al. (1997) report a detection of a much stronger signal *within the same region*. As pointed out by Leitch et al., this discrepancy could be explained by the presence of a hot component of the ISM, say around $T \sim 10^6$ K (see Eq. [4]), bringing up the second question posed in the introduction. It is important to realize that this temperature corresponds to the virial temperature of the Galactic halo; thus, we could be seeing some evidence for a hot medium in the halo of our Galaxy, or perhaps in the Local Group. This possibility may be constrained by X-ray observations, as discussed by Smoot (1998).

Attempting to clarify the nature of the dust/free-free relation, Kogut (1997) compared the Reynolds et al. (1992) patch with the DIRBE maps and found a significant correlation. This is the best way to try and answer our first question concerning the dust/free-free correlation, because the Hα gives information on the total free-free emission. Looking at Kogut’s figure 2, it is clear that there remains a significant variation around the regression line. This could represent a non-correlated component of bremsstrahlung contributing a signal perhaps as large as the correlated component. If so, dust emission would not be sufficient to trace and remove all of the free-free foreground.

### 2 A New Fabry-Perot Hα Study

In this section, we present our recent observations in Hα taken near the South Pole CMB data sets. For a complete description of the instrument, see Amram et al. (1991).

#### 2.1 Observations

The observations were made from the ESO site at La Silla (Chile) in November 1996 with a 36 cm telescope equipped with a scanning Fabry–Perot interferometer. The field of view is $38' \times 38'$, the spectral sampling step was either 5 km s$^{-1}$ or 2.5 km s$^{-1}$ (i.e. 0.10 Å or 0.05 Å),
depending on the scanning process adopted (24 or 48 channels over the free spectral range of 115 km s$^{-1}$, i.e. 2.5 Å, of the Fabry–Perot interferometer). The lines passing through the 8 Å FWHM filter were: the Galactic H$\alpha$ line we are looking for, the geocoronal H$\alpha$ emission and the OH night–sky line at 6568.78 Å. These two parasitic lines are brighter than the Galactic H$\alpha$ line we are looking for, the geocoronal line being typically twice as bright as the OH line and 10 times brighter than the Galactic line. In order to compare the Galactic H$\alpha$ emission fluctuations with the South Pole CMB results (Schuster et al. 1993; Gundersen et al. 1995), we selected fields at declinations of $-63^\circ$ and $-62^\circ$. Our fields were separated by 15 min in right ascension, which is about 1°45′ on the sky, thus offering a fair coverage of each exposed band. We observed 19 fields at $-62^\circ$ (from $\alpha = 23^h 50$ to $\alpha = 4^h 20$) and 5 fields at $-63^\circ$ (from $\alpha = 1^h 35$ to $\alpha = 2^h 50$). Some of these fields were observed twice, on different nights, to check the reproducibility of our measurements. The observing conditions were fairly good, and a standard 2h exposure time was adopted.

2.2 Data reduction

Due to the “wrap–around” nature of the FSR (Free Spectral Range) of the Fabry-Perot interferometer (FSR=2.52 Å), the OH night sky line at 6568.78 Å appears closer to the H$\alpha$ lines (geocoronal and Galactic) than it actually is, with an apparent separation of only 1 Å with respect to H$\alpha_0$ (see Fig. 1). The motion of the earth around the sun and the motion of the sun in the galaxy were combined in such a manner that the separation between the Galactic and geocoronal H$\alpha$ lines remained approximately constant, around 0.5 Å, along the bands of sky observed in November. The extraction of Galactic H$\alpha$ emission is not easy, since it is typically 10 times fainter than the parasitic lines, whose width (FWHM around 0.35 Å) and shape (not far from gaussian) also tend to bury the Galactic signal in their wings. To improve the signal–to–noise ratio and the spectral resolution, we selected a 30′ diameter disk centered on the interference rings observed in each field. The H$\alpha$ emission profile obtained for each observed field is thus the addition of the profiles of all pixels (about 31000) found within 15′ from the center of the field.

The OH night–sky line at 6568.78 Å is in fact the sum of two close components of the same intensity, one at 6568.77 Å and the other at 6568.78 Å. More complicated is the case of the geocoronal emission line, with not less than seven fine structure transitions. The two main components, produced by Lyman $\beta$ resonance excitation, are found at 6562.73 Å and 6562.78 Å, with 2:1 ratio (Yelle & Roesler 1985). However, these two components were insufficient when we decomposed our observed profiles, a residual remaining systematically at 6562.92 Å. This is due to cascade excitation which is particularly strong for the 7th component at 6562.92 Å (Nossal 1994). Although the cascade contribution is not accurately known, it proved satisfactory to use the Meier Model cited in Nossal’s thesis, adding a component at 6562.92 Å with a 1:6 ratio compared with the brightest component at 6562.73 Å.

After subtraction of the night–sky lines, a residual was found at the expected velocity for Galactic H$\alpha$ emission, that is to say, around zero in $V_{LSR}$ (radial velocity in the local standard of rest), and with the expected width, around 35 km s$^{-1}$, according to Reynolds (1990). Fig. 1 shows an example of a profile decomposition for one of our fields, together with the gaussian
Figure 1: LEFT: -Top- Example of the decomposition of the observed line profile into geocoronal Hα emission (3 components) and OH night–sky line. The remaining signal (thick line) shows the Galactic Hα emission. -Bottom- Best fit of the same Galactic Hα emission, amplified 20 times, by a gaussian. The shift with respect to 0 km s$^{-1}$ heliocentric velocity is explained by the motion of the sun with respect to the LSR. RIGHT: Geocoronal Hα (squares + dotted), OH (triangles + dashed) and Galactic Hα (stars + solid) line intensities as a function of -Top-right ascension (2000); -Bottom- mean observing time (UT). The effect of the solar depression angle is visible. Circled symbols represent the fields at a declination -63°; the other fields are at declination -62°.
2.3 Results

We find that the Galactic Hα emission along the observed bands, at $-62^\circ$ and $-63^\circ$, varies between 0.2 R and 1.4 R, in agreement with intensity values measured by Reynolds (1990) in the northern hemisphere far from the galactic plane. Fig. 2 shows the measured intensity for the Galactic Hα emission along the two declination bands. The error bars are the average rms difference between the signal and the fitted gaussian, found to be 0.35 Rayleigh. Reynolds (1990) gives intensities of the Galactic Hα emission with an uncertainty of 0.4 Rayleigh.

Fig. 2 suggests that the overall variations are faint and that the galactic Hα emission varies smoothly along the two bands of sky we observed. For a gas with $T_4 = 1$, the magnitude of the implied temperature variations at CMB frequencies is much smaller than observed in the South Pole data sets. A visual comparison is made in the right–hand panel of Figure 2, where we compare the total Hα intensity with the CMB differences.

3 Summary

To summarize the current status of our understanding of Galactic free–free emission, we would say that although there is no indication of fluctuations large enough to pose serious difficulties for CMB observations, the observational constraints remain weak. A critical interpretation of the results in the tables would be that the limit on large scale free–free fluctuations is the same order as the CMB amplitude on these same scales (at 40 GHz). On smaller scales, observations in Hα have not turned up any signs of large amplitude variations, but those based on high

Figure 2: LEFT: Solid error bars: Hα intensities measured at declination $-62^\circ$. Dotted error bars: Hα intensities measured at declination $-63^\circ$. RIGHT: Comparison of the South Pole results with the free-free emission signal deduced from our Hα observations.
resolution spectrographs are few and cover only a small percentage of the sky. There does appear to be a dust/free–free correlation on all angular scales, but there is room, and perhaps tentative indications of, an equally important non–correlated component (question #1 posed in the introduction). And then there is the puzzling result from Leitch et al. (1997), perhaps pointing to a hot phase of the ISM which could, due to lack of sensitivity, escape many of the present $H\alpha$ limits (question #2 posed in the introduction).

Obviously, CMB observations at higher frequencies, where much of the effort is now being concentrated, will suffer less from any possible free–free contamination, and the many of the next generation CMB experiments have a wide spectral coverage to aid the removal of foregrounds. Even given the above critical viewpoint, it would be a surprise to discover free–free emission presenting an important difficulty for all planned CMB experiments, at least in terms of measuring the variance, or power spectrum, from the early Universe. Foregrounds will, however, be much more important for higher order statistics looking for non–gaussian signatures. In such cases, the non–gaussian foregrounds will have to be removed to high precision. A sensitive, high spectral resolution H$\alpha$ survey of the entire sky would be of great value in the context of the above considerations.

We have also reported some results from our recent H$\alpha$ observations taken with a Fabry–Perot system at La Silla. The data cover two bands along which the South Pole data sets show significant fluctuations in CMB brightness. The observed H$\alpha$ fluctuations indicate that the CMB results in this region are not significantly contaminated by free–free emission (assuming a gas with $T_4 = 1$).

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