Abstract: This document provides a brief summary estimate of Galactic free-free emission and Hα emission and their relationship. Particular emphasis is placed on estimating the potential free-free emission in the region of significant confusion for CMB anisotropy measurements. Existing x-ray, ultraviolet and Hα emission provide limits on the radio free-free emission and vice versa. These limits are generally somewhat smaller than the observed “free-free” (signal \( \propto \nu^{-2.15} \)) microwave signal. If these preliminary results true, then some previously neglected source may be present. Physics argues that Hα emission is still the best tracer for Galactic free-free emission and thus a tool for diagnosing if there is a previously neglected source.

1 INTRODUCTION

Free-free emission is the least well known of the three diffuse Galactic emissions which dominate the mm and cm wavelength sky. Figure 1 shows versus frequency the approximate relative intensity of the Galactic synchrotron, free-free, and dust emission in relation to the cosmic microwave background (CMB).

![Graph showing frequency dependence and approximate relative strength of Galactic synchrotron, free-free, and dust emission as well as that of the cosmic microwave background and its features.](image)

Figure 1: Graph showing frequency dependence and approximate relative strength of Galactic synchrotron, free-free, and dust emission as well as that of the cosmic microwave background and its features.
2 Free-Free Emission

Radio-frequency free-free emission arises from the interaction of free electrons with ions, and consists of thermal bremsstrahlung radiation. Free-free emission is the bremsstrahlung (braking radiation) that occurs when a fast charged particle (in this astrophysical case thermally hot electrons) is accelerated in an encounter with an atom, molecule, or ion. Free-free emission is so named since the electron starts in a free (unbound) state and ends in an unbound state as opposed to being captured into a bound state (free-bound emission) or making a transition from one bound level to another (bound-bound emission). When the electron enters the Coulomb field, it is accelerated and emits radiation in a readily calculable manner. In an astrophysical plasma, such as those that exist in our Galaxy one must integrate over the total distribution of electrons and ions to obtain an expression for the volume or line of sight emissivity. The velocity averaged Gaunt factor \( < g_{\text{ff}} > \) takes into account the distributions and the quantum mechanical cutoff in scattering emission.

The volume absorptivity/emissivity of a plasma for electron-ion bremsstrahlung is \([13], [20]\)

\[
\alpha_{\nu} = \frac{4e^2}{3m_ehc} \left( \frac{2\pi}{3km_e} \right)^3 N_e N_i Z^2 T_e^{-1/2} \nu^{-3} (1 - e^{-h\nu/kT_e}) < g_{\text{ff}} >
\]

\[
= 3.7 \times 10^8 Z^2 N_e N_i T_e^{-1/2} \nu^{-3} (1 - e^{-h\nu/kT_e}) < g_{\text{ff}} >
\]

\[
\approx \frac{4e^2}{3m_ehc} \left( \frac{2\pi}{3km_e} \right)^3 N_e N_i Z^2 T_e^{-3/2} \nu^{-2} < g_{\text{ff}} >
\]

\[
= 0.018 Z^2 N_e N_i T_e^{-3/2} \nu^{-2} < g_{\text{ff}} >
\]

where the approximation is for \( h\nu \ll kT_e \) and \( < g_{\text{ff}} > \) is the velocity averaged Gaunt factor. Integration along the line of sight gives the formula for the optical depth \( \tau_{\nu} \) to free-free as

\[
\tau_{\nu} = 0.018 T_e^{-3/2} \nu^{-2} \int N_e N_i dl < g_{\text{ff}} > = 0.018 T_e^{-3/2} \nu^{-2} EM < g_{\text{ff}} >
\]

\[
= 0.0543 T_e^{-1.5} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-2} \left( \frac{EM}{\text{cm}^{-6} \text{pc}} \right) < g_{\text{ff}} >
\]

\[
\approx 0.08235 T_e^{-1.35} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-2.1} \left( \frac{EM}{\text{cm}^{-6} \text{pc}} \right)
\]

where the emission measure \( EM \) is defined as: \( EM \equiv \int N_e N_i dl \). The brightness spectrum has a \(-2.1 \pm 0.03\) spectral index, with weak dependency on the temperature and density of the interstellar plasma and the observing frequency. The Gaunt factor accounts for this small dependency.

This formula (Eqn. 7) is based on the assumptions that the interstellar plasma is electrically neutral, that the temperature of the electrons along the line of sight is roughly constant, that the electron temperature is greater than 20K, the frequency is smaller than 100 GHz, and that the Gaunt factor can be expressed as a product of powers of the frequency and the electron temperature. \([8], [20]\).

An estimate of the brightness temperature for free-free emission can be found from the radiative transport equations

\[
T^\text{ff}_b = T_e (1 - e^{-\tau_{\nu} T_e}) \approx \tau_{\nu} T_e
\]

\[
\approx 5.43 \mu K \left( \frac{10 \text{ GHz}}{\nu} \right)^2 \left( \frac{10^4 K}{T_e} \right)^{1/2} \left( \frac{EM}{\text{cm}^{-6} \text{pc}} \right) < g_{\text{ff}} >
\]

\[
\approx 26 \mu K \left( \frac{10 \text{ GHz}}{\nu} \right)^{2.1} \left( \frac{10^4 K}{T_e} \right)^{0.35} \left( \frac{EM}{\text{cm}^{-6} \text{pc}} \right)
\]

An approximation for the velocity-averaged Gaunt factor \( < g(\nu, T_e) > \) is \([20]\):

\[
< g_{\text{ff}} > \approx 4.69 \times [1 + 0.176 ln(T_e/10^4 K) - 0.118 ln(\nu/10 \text{ GHz})]
\]

detail tables and formula can be found many places \([8], [20]\).
3 Free-Free Signal

Free-free emission is the least well known of the Galactic emissions. It is not easily identified at radio frequencies, except near the Galactic plane. At higher latitudes free-free emission must be separated from synchrotron emission by virtue of their differing spectral indices. At frequencies less than about 10 GHz synchrotron emission dominates at intermediate and high latitudes. At higher frequencies where free-free emission might be expected to exceed the synchrotron component, the signals are weak and survey zero levels are indeterminate.

4 Hα Emission

At present most of the information currently available about the source of free-free radiation at intermediate and high latitudes comes from Hα surveys.

4.1 Relation between Hα & Free-free Emission

Diffuse Galactic Hα is thought to be a good tracer of diffuse free-free emission since both are emitted by the same ionized medium and both have intensities proportional to emission measure (the line of sight integral of the free electron density squared, \( \propto \int N_e^2dl \)).

The intensity of Hα emission is given \([16],[11]\) by
\[
I_\alpha = 0.36R \left( \frac{EM}{cm^{-6}pc} \right) \left( \frac{T}{10^4 K} \right)^{-\gamma} \tag{12}
\]
for \( T \leq 2.6 \times 10^4 K \) and where \( \gamma \) varies from 0.9 for \( T_e \leq 2.6 \times 10^4 K \) to 1.2 for \( T_e > 2.6 \times 10^4 K \),

\[
1R \equiv 1\text{Rayleigh} = \frac{10^6}{4\pi} \text{photons/(cm}^2\text{s ster}) = 2.41 \times 10^{-7} \text{ergs/(cm}^2\text{s ster)} \tag{13}
\]
at a wavelength \( \lambda_{H\alpha} = 6563 \) Angstroms.

Combining the free-free and Hα equations one finds a relation between the low-temperature Hα intensity and the free-free emission
\[
T_{b}^{ff} = 1.68\mu K < g_{ff} > \left( \frac{T}{10^4 K} \right)^{0.4 \text{ to } 0.7} \left( \frac{\lambda}{1 \text{ cm}} \right)^{2.1} \left( \frac{I_\alpha}{R} \right) \tag{14}
\]
\[
\approx 7\mu K \left( \frac{T}{10^4 K} \right)^{0.55 \text{ to } 0.85} \left( \frac{\lambda}{1 \text{ cm}} \right)^{2.1} \left( \frac{I_\alpha}{R} \right) \tag{15}
\]
so that for example \( T_{b}^{ff}(30 \text{ GHz}) = 7\mu K (I_\alpha/R) \), \( T_{b}^{ff}(45 \text{ GHz}) = 3\mu K (I_\alpha/R) \), and \( T_{b}^{ff}(53 \text{ GHz}) = 2\mu K (I_\alpha/R) \). A typical measured value for \( I_\alpha \) is order of 1 \( R \).

4.2 Results from Hα Surveys

The major Hα structures form the well-known Local (Gould Belt) System which extends 30°-40° from the plane at positive \( b \) in the Galactic centre and at negative latitude in the anticentre. The HI and dust in the Local System may be traced to 50° from the Galactic plane. Other Hα features are also found extending 15°-20° from the plane \([23]\).

Quantitative measurements are now available from accurate spectroscopy (e.g. Reynolds 1992, Bartlett et al. 1997). To first order the Hα may be approximately modelled as a layer parallel to the Galactic plane with a half-thickness intensity of 1.2 Rayleigh (R). The rms variation in this Hα emission is roughly 0.6R on degree scales.

The four-year COBE DMR sky maps at different frequencies have been utilized to isolate emission with antenna temperature which varies proportional to frequency to the -2.15 power (\( \propto \nu^{-2.15} \)) \([8]\) in an attempt to provide a large angular scale map of free-free emission at 53 GHz. This low-signal to noise
map is consistent with the Hα large scale model with a free-free half height amplitude of $10 \pm 4 \mu K$. The rms free-free signal on a $7^\circ$ scale was estimated to be $\Delta T_{ff} = 7 \pm 2 \mu K$.

The Hα images of the NCP area made by Gaustad et al. (1996) have been analyzed by Veeraraghavan & Davies (1997) to provide an estimate of the spatial power spectrum on scales of $10^\prime$ to a few degrees. The power law index is $-2.3 \pm 0.1$ over this angular range. The rms amplitude is $0.12 \csc(|b|)$ Rayleighs on 10 arcmin scales.

It has been assumed that the free-free component could be modeled using measurements of Hα emission, (e.g. [22], [18]) which measure the density of free electrons. However, recent results showing more significant correlation of dust and apparent free-free emission have been interpreted as presenting us with a surprise [9][3][11]. Alternative explanations have been suggested including rotating dust grains [5]. It still appears that mapping the Hα emission is the best way to determine the free-free emission and separate out any other component.

Although Galactic Hα emission is correlated with the Galactic free-free emission, it is not straightforward to estimate the Galactic free-free emission from the Hα sky maps. The Hα sky maps are contaminated with Hα from the Earth’s geocoronal emission. The geocoronal emission varies both diurnally and seasonally with the solar Lyman/β flux. This variation ranges from 2 to 25 Rayleigh.

The geocoronal and Galactic Hα emissions are separable in principle, since the Doppler shift of the Earth’s motion around the solar system separates the lines. Making this separation requires spectral measurements and is less effective as one moves toward the ecliptic poles where the separation is negligible. There is also the issue of another atmospheric line (OH) that partially blocks the positive Doppler shift side so that only during restricted seasons can part of the geocoronal effect be removed well in this manner.

5 Galactic Corona and High Temperature Regions

The ROSAT 1/4 keV survey of the soft x-ray background is being used to map out the hot gas in the local bubble but more importantly to show the existence of the long hypothesized [25] hot Galactic corona.

In 1956 Spitzer [25] suggested that the Galactic halo was filled with hot gas. A primary argument was the existence of cool gas clouds high above the Galactic plane, which he reasoned must be confined by a hotter ambient medium. This hot medium must be continually being resupplied with energy as cooling would soon set in. The favored current model is of fountains of hot ionized material produced by large groups of supernovae.

The dust in the Draco complex appears as a “shadow” in the soft x-ray background providing direct evidence that a large portion of the soft x-ray background comes from the Galactic halo. The ROSAT soft x-ray data and HI maps have been used to model the hot ionized interstellar medium, e.g. [21], to obtain estimates of the temperature and emission measure $(EM)$.

The x-ray temperature estimates are on the order of $10^{6.2 \pm 0.2}$ K which are consistent with the predictions based upon the virial temperature $T_{virial} \sim 2 \times 10^6$ K of the halo.

6 Emission form the Magellanic Stream

The Magellanic Stream is a long filament of H I clouds which stretches over $100^\circ$ across the sky which trails behind the Magellanic Clouds in their orbit around the Galaxy [12]. In ram pressure explanations for the origin of the Magellanic Stream, the Stream is swept out of the Magellanic Clouds by the diffuse ionized corona of the Galactic halo. The Stream is a chain of clouds connected by lower-density gas.

These clouds generally have a high-density concentration and gradient on the leading edge [3] and Hα emission is observed on some of these clouds [30]. The Hα emission is best explained by ram pressure heating from the hot Galactic corona.
Table 1: Estimates of Hα & Free-free emission

| Region                        | T (K) | EM (cm⁻⁶pc) | Iα (R) | Tff (30 GHz) |
|-------------------------------|-------|-------------|--------|--------------|
| Local Bubble                  | 10²⁵.⁹ | 0.004 [2]   | 3 × 10⁻⁵ | 10⁻³         |
| Disk Region (~ 1 kpc)         | 10⁴   | 2.9 csc|b| [16] | 1 | 5 - 40 |
| Halo                          | 10⁶.²  | 0.024 [2]   | 9 × 10⁻⁵ | 7 × 10⁻³ |
| Magellanic Stream             | 10⁴   | 0.5-1.0 [30]| 0.2-0.37±0.02| 2-4         |
| Local Group Corona            | ~ 10⁶ |             |        | ~ 0.1       |

7 Estimates of Free-Free Emission

Table 1 presents measurements and estimates of the Galactic ionized emission regions. Using the formulae relating the free-free emission to the plasma temperature and emission measure and to Hα emission one derives the signals shown. The numbers for the Galactic free-free emission derived this way are a factor of two below what one finds using the slope (fitting to csc|b|) COBE DMR free-free map. The DMR free-free map does not have a strong signal-to-noise ratio and shows a high degree of correlation with the Galactic dust emission [9] which may or may not be free-free emission [5]. For that reason it is more reliable and consistent to trace the properties of the ionized interstellar medium through its Hα emission. The major question is: How much hot (T >> 10⁴ K) gas is there in the interstellar medium? Could there be enough to make up the factor of two? The x-ray and pulsar dispersion measurements put a tight limit on the possible additional free-free emission. The pulsar dispersion measurements are consistent with an emission measure of approximately 1 csc|b|/(cm⁻⁶pc) if all the ionization is spread evenly and uniformly. The estimate is higher by the fractional filling factor. The filling factor is estimated to be of order 0.1 to 0.4, increasing with increasing Galactic latitude.

8 X-ray Emission Information

The volume emission by thermal bremsstrahlung is

\[
\frac{dE}{dtdνdV} = \left(\frac{32πe^6}{3m_e^3}\right)\left(\frac{2π}{3km_e}\right)^{1/2}T_e^{-1/2}Z^2e^{-hν/kT_e} < gff >
\]

Integrating over the line of sight one finds

\[
\frac{dE}{dtdνdA} = 6.8 × 10^{-38} \int N_eN_idl T_e^{-1/2}Z^2e^{-hν/kT_e} < gff > \text{ ergs}^{-1}\text{cm}^{-3}
\]

X-ray emission is a good tracer of radio free-free emission when the plasma is sufficiently hot to produce x-rays via thermal bremsstrahlung. That is they both arise from the same mechanism but are the opposite extremes of \(hν/kT_e\). Thus they have essentially the same coefficients except the Boltzmann suppression factor is very important for x-rays. One can then use the x-ray observations to provide an estimate and upper limit versus temperature for the radio free-free emission.

A summary of the observations, Hα prediction, and the x-ray limits are shown in Figure 3. (Note that the OVRO [11] observations of about 200 µK at 14.5 GHz extrapolate to be roughly 13 µK at 53 GHz;
Figure 2: Graph showing frequency dependence and estimated signal levels of Galactic free-free emission for medium and high latitudes as a filled band and an open band for the Magellanic Stream clouds as well as that of the cosmic microwave background and its features.

however, since the signal is at such a small angular scale, one would have predicted a smaller number by a factor of roughly 10.)

9 Ultraviolet Observations

Current Hα and x-ray observations leave room for plasma in the $T_e \sim 10^5$ K range to produce significant radio free-free. One would not be surprised that a rising Galactic fountain of hot supernova gas would cool from $10^6$ K to this level. However, measurements in the ultraviolet can constrain this possibility. Ultraviolet observations of O VI indicate the presence of halo hot gas in the temperature range $5.3 \leq \log(T_e) \leq 5.8$. The mean density of the gas is of order $0.01 \text{ cm}^{-3}$ with scale height of less than 1 kpc and filling factor greater than 0.1. This can be used to limit the radio free-free emission. This limit is generally below 0.1 $\mu\text{K}$. The plot in Figure shows a significantly higher limit both to be very conservative and so that the limit would show on the plot.

10 Geocoronal Free-free & Hα Emission

The Earth’s corona produces Hα emission. About 12% of the hydrogen atoms excited by solar Lyman $\beta$ photons return to their ground state through the emission of Hα photons. This geocoronal emission varies both diurnally and seasonally with the solar Lyman $\beta$ flux. The amplitude variation ranges from
Table 2: Correlation of Dust vs Free-free & Hα Emission

| Authors             | $T_{ff}/I_{100\mu m}$ | Frequency $\ell$ | $b$ | $|b| > 20^\circ$ |
|---------------------|------------------------|-----------------|-----|-----------------|
| Leitch et al. [11]  | 75                     | (µK (MJy/sr)$^{-1}$) | (GHz) | (deg) |
| Kogut et al. [9]    | 18.06 ± 2.54           | 31.5            | 53  | NCP            |
| Costa et al. [3]    | 15.0 ± 8.1             | 40              | NCP |                 |

| Authors             | $I_{H\alpha}/I_{100\mu m}$ | Frequency $\ell$ | $b$ |
|---------------------|-----------------------------|-----------------|-----|
| Kogut 1997 [10]     | 0.85 ± 0.44                 | Hα              | 144°|
| Kogut 1997 [10]     | 0.34 ± 0.33                 | Hα              | NCP |
| McCullough [13]     | 0.79 ±0.44                  | Hα              | 71° |

Implied from Free-free $T_e \approx 10^4$ K

- Leitch et al. [11]  6  NCP
- Kogut et al. [9]    2.0 ± 0.5  50  $|b| > 20^\circ$
- Costa et al. [3]    3.6 ± 2  NCP

about 2 to 25 Rayleighs.

Geocoronal Hα emission is not expected to be a tracer of geocoronal free-free emission as most of the hydrogen is not significantly ionized but excited via solar Lymanβ. The mean temperature of the geocoronal hydrogen ranges from 900 K to 1300 K.

The geocoronal Hα emission is a potential interference for observing the Galactic Hα emission. Doppler effect allows separation because of the motion of the Earth around the Sun and the relative motion of the plasma. However, such a separation requires high resolution spectral measurement and analysis instead of simple imaging.

11 Hα & Free-Free vs. Dust Emission Correlation

A number of groups have found a significant correlation between dust and microwave “free-free” (antenna temperature spectral index $\sim -2$) emission by cross correlation between 100 µm IRAS and DIRBE maps and the observed emission [1, 11, 3, 29], and Hα-dust correlation [10, 13]. Table 2 provides a summary of results on the dust vs Hα & free-free emissions. Table 2 shows clearly that the estimated “free-free” emission correlation to the dust implies a larger total signal than the Hα. This is the same conclusion one tentatively reaches from Figure 2 which gives the predicted signal level or upper limits from the Hα, ultraviolet, and x-ray observations.

There is also an inconsistency between the estimates from the microwave estimates of “free-free” signal emission unless there is significantly more correlation between the “free-free” signal and the dust emission at smaller angular scale.

12 Conclusions

The estimation of radio (e.g. 53 GHz) free-free emission is not a completely settled issue. It is possible that some of the signal seen is due to rotating dust or some other no yet understood source. However, it is possible that the signal level and the correlation with dust will be readily accounted for by simple emission from warm ($T_e \sim 10^4$ K) plasma which is well traced by its Hα emission. The issue will be
resolved when there are both high quality Hα and microwave observations and the results can be carefully cross correlated. At that point we will be able to determine what is the level of the other sources.

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Figure 3: Graph showing plasma temperature dependence of the predicted 53 GHz free-free emission antenna temperature for the mean observed Hα emission (1.2 R). Also shown is the limits derived from x-ray and extreme ultraviolet emission and the fit to the COBE DMR observations.