HCNE Science Implementation Document

The Herschel Confusion Noise Estimator

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Chapter 1. Confusion noise in general

By definition, *confusion noise* is the uncertainty in the determination of point source flux due to the uncertainty in the determination of the background flux. To contribute to the confusoin noise, the background has to be stohastic, i.e. it has to change from one place to the other in an unpredictable way (a random field). A background may be intrinsically diffuse (like the interstellar medium) or may be the accumulated light of unresolved sources (like the extragalactic background, see below). The sky backgrounds are usually composed of several components.

The first mathematical description of confusion noise was introduced in the 1970's in radio astronomy (Condon 1974), and described the common effect of an ensemble of discrete point sources for the measurement uncertainty of single sources. There are two important criteria to clearly detect a point (or compact) source: the source flux has to be well above the average fluctuation amplitude of the background (photometric criterium) and the source has to be far enough from sources of similar brightness so that they could be detected individually (source density criterium). These two criteria together set the *confusion limit*: above this level compact sources can be clearly detected (see e.g. Dole et al. 2003, for an introduction).

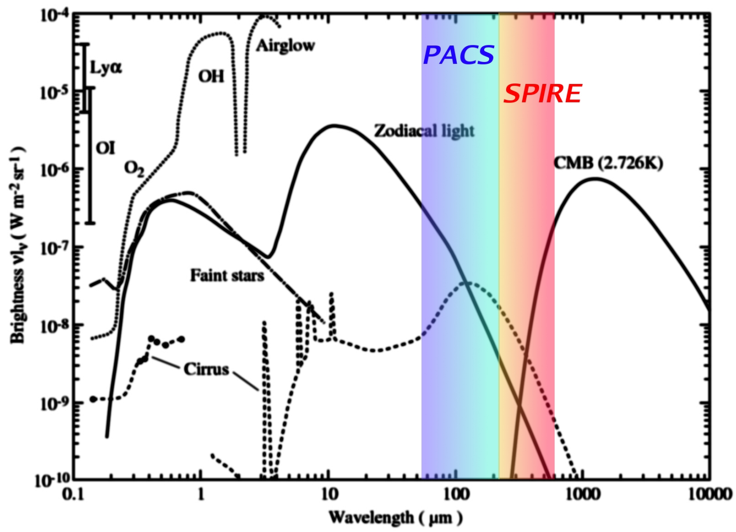
In typical optical measurements the confusion limit is not encountered. Exceptions are e.g. the dense star clusers, where the source density criterium is matched. In the infrared, confusion limits, especially the photometric criterium, often have a serious impact on the measurements. This is partly due to the characteristics of infrared detectors -- especially their poor resolving power compared to those working in the optical -- and partly due to the astrophysical properties of the infrared sky background. It has to be noted, that the interpretation of confusion noise is different in an unbiased survey (when we want to detect all sources above a certain limit) and when observing an individual source, that is known to exist at a certain sky position (and is detected e.g. at shorter wavelengths). In the latter case it is possible in certain conditions to integrate below the confusion limit set by the whole ensemble of sources.

Chapter 2. The far-infrared sky

In the infrared the sky background is strong compared to the brightness of typical sources, and as a consequence, the confusion noise caused by these background components is also relatively strong. The infrared sky have to following main components (see Fig. 2.1):

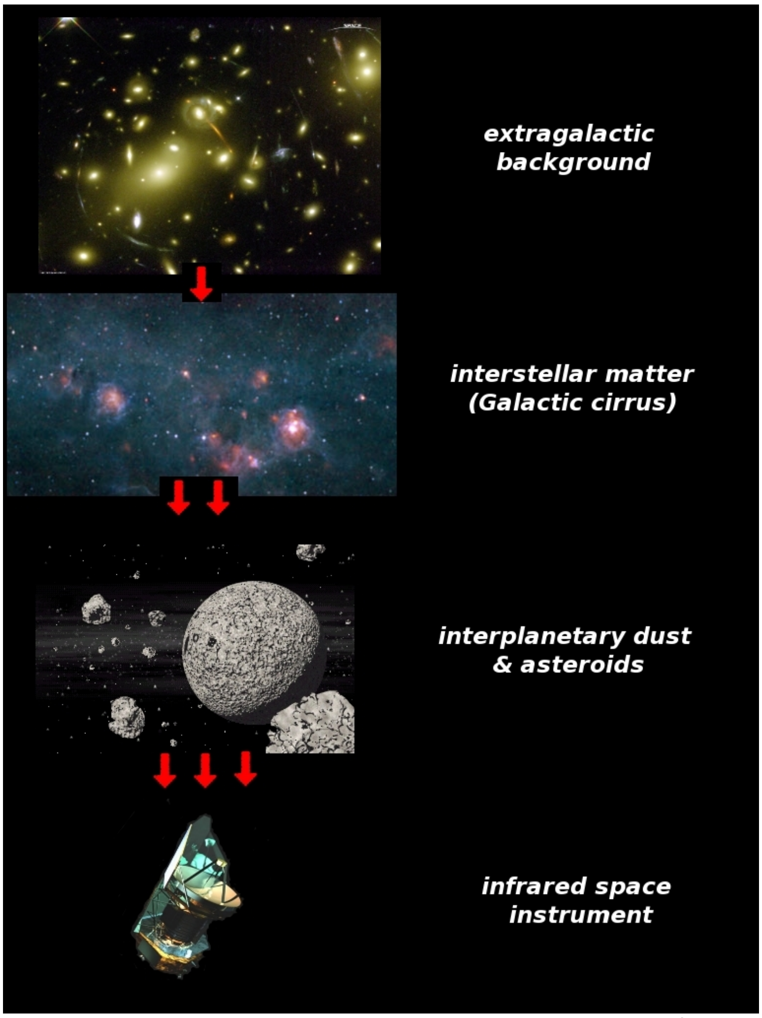
1. Emitting particles in Earth's atmosphere (specific ions, molecules and airglow). For space-born instruments these effect are do not play a role.
2. Faint stars in the Milky Way. This is an important component for near- to mid-infrared wavelenghts, but has a negligible contribution for longer wavelengths, e.g. those of PACS and SPIRE.
3. Zodiacal Light and minor bodies in the solar system. This is the dominant component of the sky background at MIR wavelengths.
4. The Galactic cirrus emission -- quasi-thermal emission of dust in weak gas clouds in the Milky Way. This is the dominant component for wavelengths λ>70µm.
5. The extragalactic background -- accumulated and unresolved light of distant galaxies.
6. The cosmic microwave background also have an important contribution in strength, but the fluctuation amplitudes are small, and well below the detection limits of PACS and SPIRE.

For space-born FIR and submm instruments the important confusion noise components are astro-physical. These are (1) dust and minor bodies in the solar system, (2) the Galactic cirrus emission, (3) and the extragalactic background (see Fig. 2.2).



Brightness of the night sky as seen from the ground, without the contribution of the extragalactic background (Leinert et al. 1998). The spectral range covered by the PACS and SPIRE instruments of the Herschel Space Observatory are indicated.

Figure 2.1. Components of the sky brightness



The main contributors to the sky background and to the confusion noise in the far-infrared for a spaceborn instrument.

Figure 2.2. Main components of the far-infrared confusion noise

Chapter 3. Sources of FIR emission in the Solar System

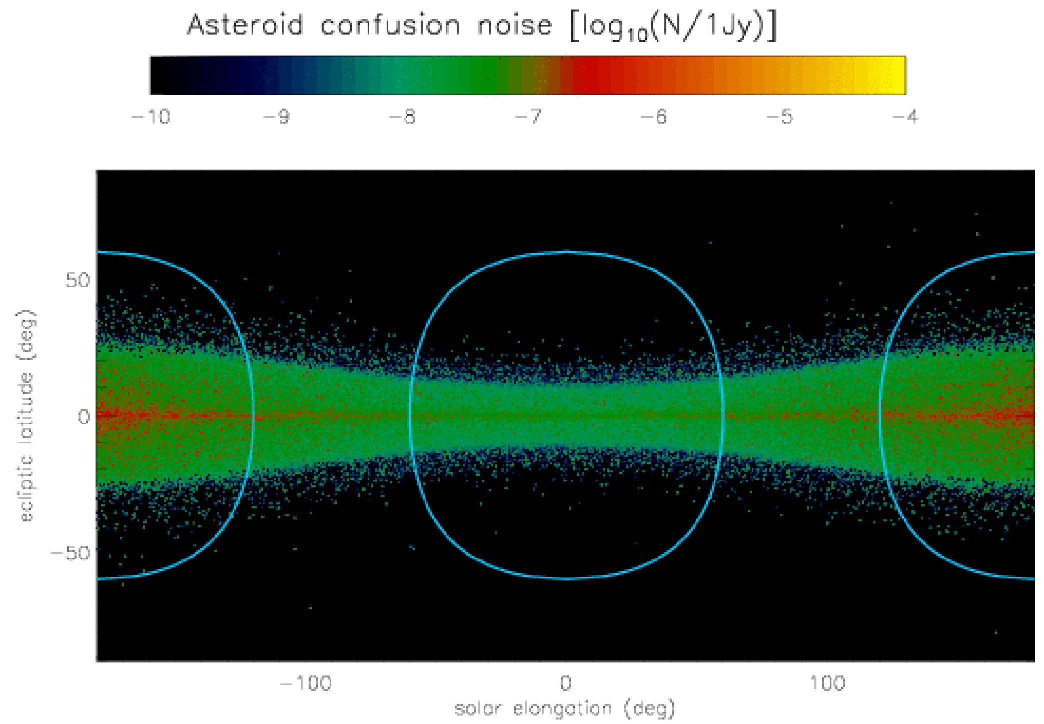
There are two major sources of FIR and submm emission in the Solar System that can contribute to the confusion noise. These are the thermal emission of dust particles of the Zodiacal Light nebula, and the thermal emission of the asteroid populations.

The zodiacal light emission is a major contributor to the sky brighness throuhout the infrared wavelength regime, with a superior contribution in the mid-infrared. The declining spectral energy distribution towards longer wavelengths make the ZL emission less important for the FIR and submm wavelengths. Moreover, this emission is quite smooth, and small-scale fluctuations -- which are necessary to produce confusion noise -- are not present in the ZL nebula, at least at or above the arcminute scale angular resolutions reached by ISOPHOT, as was shown by Ábrahám et al. (1997). Smaller scale fluctuations, in principle, are likely to exist, but the presence of such structures were *not* yet confirmed by recent observations of the Spizter Space Telescope (see e.g. the Spitzer GO program "The Production of Zodiacal Dust by Asteroids and Comets" by M. Sykes). Therefore, currently no contribution of ZL confusion noise is considered in the Herschel Confusion Noise Estimator. However, this is a field of active research, and new results may be implemented in the HCNE in later versions.

It is an important question whether faint asteroids, which are individually below the detection limits, could contribute significantly to the confusion noise of space-born FIR and submm instruments, especially those of Herschel. In a recent work Kiss et al. (2006) investigated this issue. In order to take into accound these asteroids, a reliable statistical model was needed, including minor bodies smaller than a few kilometers in diameter. Recently Tedesco et al. (2005) presented the "Statistical Asteroid Model" (hereafter SAM). This model is based on a population of ~$1.9\text{x}10^6$ asteroids obtained from the complete known asteroid sample (as of 1999), plus extrapolation of the size-frequency distribution (SFD) of 15 asteroid dynamical families and three background populations, to a diameter limit of 1km. The validity of the SAM was demonstrated by comparing SAM predictions with ISO measurements at 12µm (Tedesco and Desert, 2002) and Spitzer measurements at the 8µm and 24µm bands (Meadows et al., 2004). Asteroid counts from both surveys show good agreement with the SAM predictions.

Spatial and sky positions of all asteroids were calculated for a the time period from 2000 January 1 to 2012 December 31, with a time resolution of 5 days. This step size was sufficient to give a good coverage of solar elongations. For the brightness calculations the Standard Thermal Model (STM; Lebofsky et al. 1986) was applied. A grid of 0.5'x0.5' cells was defined in the sky (in ecliptic coordinates), and asteroid counts above specific flux limits were determined for each cell, as well as the confusion noise due to asteroids in that particular cell. The confusion noise was calculated from the 'observed' distribution of all asteroids in that specific cell for each wavelength. These confusion noise values are *lower limits* since there is an unknown contribtuion of small (fainter) asteroids, which were considered. However, bright asteroids are the dominant sources of confusion and asteroids smaller than ~1km in diameter would not contribute to the confusion noise significantly.

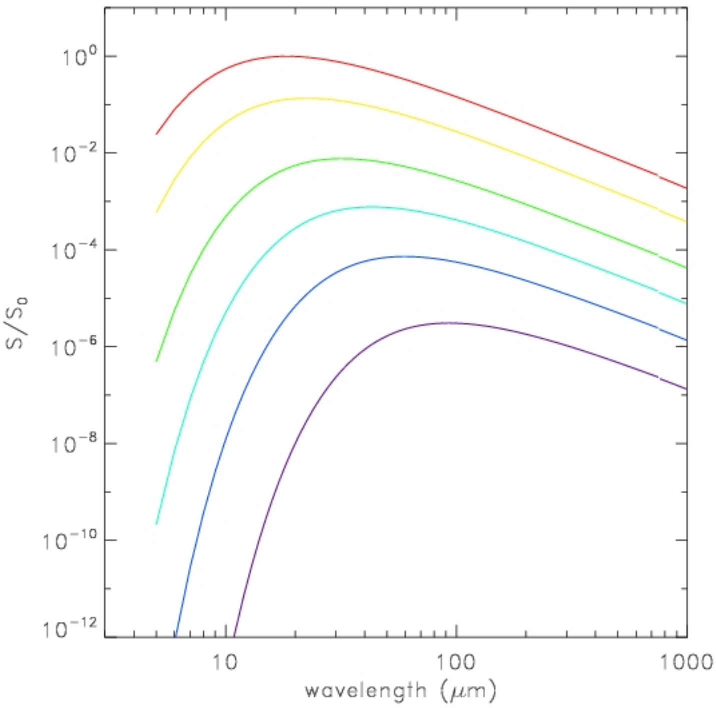
Using these model calculations all-sky confusion noise maps were constructed and expected number counts were calculated for the sensitivity limits of the instruments. The main trend shows a strong concentration of asteroids and a corresponding peak of confusion noise at the local anti-solar point and an extended "cloud" is present around the current maximum. Seasonal variations are also not negligible. For Herschel, asteroid confusion would not be negligible in anti-solar direction, however, solar aspect constraints for satellites usually do not allow to observe towards opposition targets (see Fig 3.1). Therefore no asteroid confusion noise component is included in the Herschel Confusion Noise Estimator.



Asteroid confusion noise, calculated for the PACS photometer red band (~175µm). Horizontal axis represent the solar elongation (λ-λ_o), while the vertical axis represent the ecliptic latitude. The Sun is in the middle of the figure at (0,0) and the anti-solar direction is at the horizontal edges of the image ((-180,0) and (180,0)). Colours represent the strength of the asteroid confusion noise, as indicated by the colour bar on the top. Although asteroid confusion may not be negligible around the anti-solar direction in some cases, Herschel will not be permitted to look in these directions due to the solar visibility constraints. These regions are indicated by blue circles in the figure.

Figure 3.1. Asteroid confusion noise for the PACS red photometric band

In Kiss et al. (2006) it was also investigated whether a colder population of asteroids (e.g. those in the Kuiper belt) can contribute more the FIR and submm confusion noise than the Main Belt asteroids considered in the SAM model. The results show that although in a hypopetical population behind the Main Belt the peak of the SEDs of the asteroids are shifted to longer wavelengths, this cannot compensate for the very fast drop in brightness due to the increasing solar and terrestrial distance of these bodies (see Fig. 3.2).



Demonstration of the effect of the increasing Earth/Sun distance on the observed fluxes of the asteroids. S/S_0 is the ratio of measured S flux value at a specific wavelength and the reference flux value S_0 (the maximum value of the spectral energy distribution at Δ=1AU). The curves correspond to (Δ=1, 2, 5, 10, 20 and 50AU, from top to bottom, respectively and r_o=Δ+1AU in all cases. Δ and r_o are the terrestrial and solar distances of the asteroids, respectively.

Figure 3.2. Spectral energy distribtuion of far asteroids

Chapter 4. Interstellar medium

The interstellar medium show a strong concentration around the Galactic plane and this feature is conspicious at many wavelengths. However, there is another component of the interstellar medium, that is not sticked to low Galactic latitudes. The Galactic cirrus emission -- discovered by IRAS (Low et al. 1984) -- is the thermal emission of dust in weak and cool interstellar HI clouds (typically $n \leq 10^2 cm^{-3}$ and $T \approx 20K$). It has a smooth modified blackbody SED with $\beta \approx 2$, with some additional infrared cooling lines. This is a strong source of emission, and dominates the sky for wavelengths $\lambda > 70\mu m$, even at high Galactic latitudes. The cirrus emission is very structured, and show a typical filamentary structure.

The main characteristic of the cirrus emission -- or in general that of the interstellar medium -- is its spatial structure at a specific wavelength. This is usually described by the spectral index, *#*, of the power spectrum of the image, averaged over annuli (see Kiss et al., 2003, for a summary). With this parameter the power spectrum is $P = P_0 \times (f/f_0)^{\alpha}$, where *P* is the power at the spatial frequency *f* and P_o is the power at the spatial frequency f_o. Due to this parametrization the structure of cirrus is equivalent to that of a fractal. The spatial structure is important in separating the cirrus from the other components of the sky background, since this is different from those of the CIB (Poissonian distribution at low spatial frequencies) or of other components. Although the SED of the cirrus emission is quite well determined in the whole sky, its shape is not very different from that of the cosmic infrared background, therefore their separation in this way is not easy.

Molecular clouds with densities significantly higher than that of cirrus show a similar fractal structure (see. e.g. Falgarone et al. 2004), therefore the cirrus structure models can easiliy be extended to higher surface brightness regions.

There are essentially two kind of approaches to characterize the confusion noise or sky brightness fluctuations of the emission from the interstellar medium at a specific sky position; both methods have their own pros and cons. Below we describe the two methods in some detail.

- In the work by Jeong et al. (2005 & 2006) the fluctuations are considered to show the same power spectrum along the whole spatial frequency range and are independent of wavelength. Jeong et al. (2005) used the SFD 100µm maps to characterize the local cirrus structure down to the resolution of IRAS. This power spectrum has been extrapolated to higher spatial frequencies, and high frequency noise is added to the original, low frequency maps. The confusion noise is calculated on these noise-coadded maps. Extrapolation to other wavelengths is done by applying a two-component dust model and the SFD 100µm emission maps. Temperatures are determined using the DIRBE 100 and 240µm measurements and fixed emissivity laws (β_1=1.67 and β_1=2.70, see Finkbeiner et al. 1999).

  The greatest advantage of the method is, that the confusion noise determination is very local, and therefore can account for local deviations of the behaviour of the cirrus emission. On the other hand it was shown in Kiss et al. (2003), that the spectral index # is different at variuos wavelengths, at least for regions of medium and high surface brightness. Since the Jeong et al. (2005) method use the SFD 100µm maps to generate power spectrum at all wavelengths, this effect is not taken into account, and can lead to unrealistic confusion noise values, especially at wavelengths significantly longer than 100µm. The main reason behind the different α at various wavelengths is the presence of a colder component (with a temperature of 15K or below) in the FIR emission. This component is hardly visible at 100µm due to its temperature and by not be accounted at all in longer wavelength maps generated from the 100µm information only.

  A further shortcoming of this method -- using SFD 100µm maps to derive the power spectrum at low spatial frequencies -- is related to the behaviour of detector responsivity of survey observations that scanned the sky with a fixed integration time (Miville-Deschenes & Lagache, 2005). For small flux changes the detector stabilization times are longer than for larger ones, therefore the amplitude of the intensity fluctuations are underestimated at low flux and at small scales (see Coulais & Abergel, 2000, for a model of detector stabilization times). This means that the power spectrum of these maps are apparently steeper than they are in reality, especially for faint fields. Power spectra taken this way underestimate the fluctuation power at the highest spatial frequencies.

This is in agreement with the results by Kiss et al. (2003), where a shallower spectrum with α # -2.3 spectral index was found for the cirrus component in fields with weak cirrus contribution, in contrast to the generally accepted value of α=-3, deduced from IRAS scans.

From the technical point of view, the calculation required to generate the maps are relatively time are resource consuming. This is acceptable for specific regions, but it may be problematic to extend this method for the whole sky.

- Kiss et al. (2001, 2003 & 2005) used a different approach to characterize the sky brightness fluctuations of the cirrus emission. The original idea was introduced and applied for IRAS scans by Helou & Beichman (1991) and by Gautier et al. (1992). In this approach the amplitude of the sky brightness fluctuations (i.e. the confusion noise) depends mainly on the resolving power of the instrument and the brightness of the local background. The confusion noise depends on a few parameters, and can be described by a simple equation. Once these parameters are known the strength of the confusion noise depends on the brightness of the local background only. Interpolation or extrapolation to other wavelengths can be done by using the wavelength scaling of the resolving power and the spectral energy distribution of the emission of the ISM (cirrus). The different structure at different wavelengths can also be taken into account.

  An important parameter of this method is the spectral index α of the cirrus structure. The most extensive investigation of this parameter has been done by Kiss et al. (2003). Based on the analysis of ISO/ISOPHOT maps at multiple wavelength, the wavelength and brightness dependence of α was determined for the spatial scales and filter bands available with ISO/ISOPHOT. Extrapolations to smaller angular scales, however, have to rely on assuptions and extrapolation of the low spatial frequency results with this method as well. In general, the cirrus confusion noise is described by an equation similar to the one below:

$$N_{cirr} = c_1 \times \left(\frac{\lambda}{D}\right)^{1-\frac{\alpha}{2}} \times B^{\eta}$$

  Here N_{cirr} is the confusion noise due to the cirrus component, B is the surface brighness of the field, α is the specrtal index of the logartihmic power spectrum, averaged in annuli (see Kiss et al. 2001, 2003 & 2005 for details), λ is the wavelength of the observation and D is the effective diamter of the telescope's primary mirror. The parameters c_1 and η has to be determined from measurements. For IRAS 100μm scans Helou & Beichman (1990) found the following relation (they applied α=-3):

$$\frac{N_{\mathrm{H\&B}}}{1\ \mathrm{mJy}} = 0.3 \times \left(\frac{\lambda}{100\ \mu\mathrm{m}}\right)^{2.5} \left(\frac{D_t}{1\ \mathrm{m}}\right)^{-2.5} \left(\frac{\langle B_\lambda \rangle}{1\ \mathrm{MJy\,sr^{-1}}}\right)^{1.5} .$$

  Kiss et al. (2003 & 2005) extended this analysis to a series of ISO/ISOPHOT bands, and obtained the parameters describing the confusion noise related to cirrus at different wavelengths. These results have been scaled to the resolution of other infrared space instruments (e.g. Herschel/PACS), assuming, that spectral index α remains unchanged for higher spatial frequencies. In these calculations the brightness-dependent spetral index (introduced by Kiss et al. 2003) was also taken into account. The most important limitation of this method is, that local deviations from the general brightness-dependence of the cirrus confusion noise are not taken into account. Once the parameters (c_1, α, and η) are known, the calculation of the confusion noise strength is easy, and very strightforward.

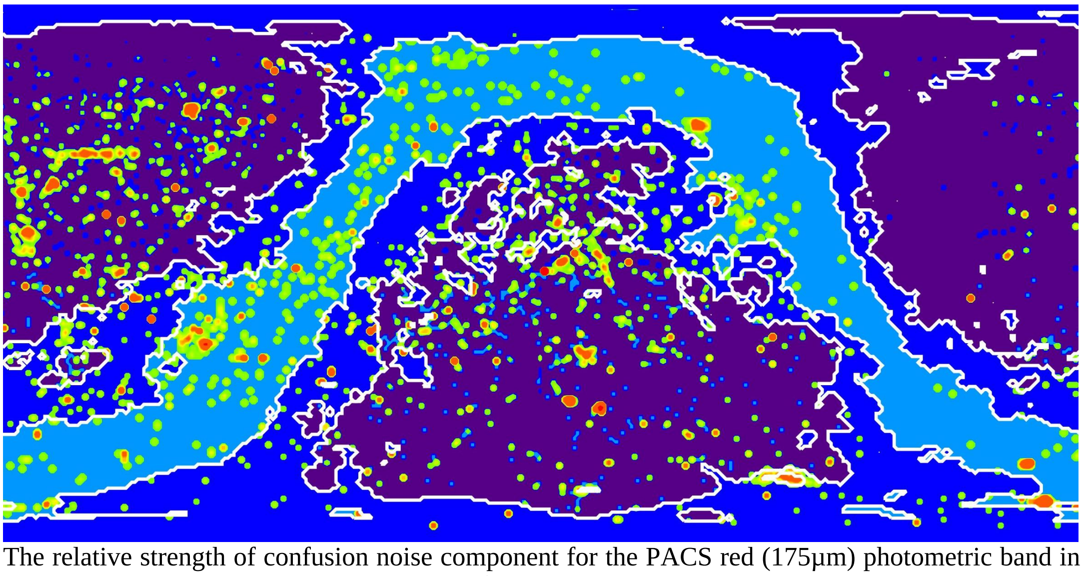
Chapter 5. The cosmic infrared background

The cosmic infrared background (CIB) is the second strongest component of the extragalactic background (the strongest being the cosmic microwave background). The extragalactic background is the accumulated light of distant, unresolved galaxies. The CIB is a relic radiation of the star and galaxy formation history of the Universe, therefore it is very important for cosmological and galaxy formation/evolution studies. Most of its light is a reprocessed starlight or other kind of radiation produced e.g. by active galactic nuclei: radiation emitted at optial, ultraviolet and X-ray wavelengths are absorbed by dust and re-emitted in the infrared due to its temperature. The shape of the CIB is also affected by the fact, that most of its building sources are fairly redshifted. In the far-infrared the strongest contribtuion comes for sources at $1 \leq z \leq 2$, and this typical z-value is even higher in the submm. A summary of efforst to detect the CIB at various wavelengths is given in Hauser & Dwek (2001), including the results obtained e.g. from DIRBE, IRAS, ISO, HST, 2MASS data. Recent results either based on reprocess satellite observatory data (IRAS: Miville-Deschenes & Lagache 2005; and ISO: e.g. Kiss et al. 2001, Dole et al. 2003) or based on the measurements of the Spitzer Space Observatory (e.g. Dole et al. 2004 & 2006; Papovich et al. 2004).

The numerous sources of the CIB are randomly distributed in the sky and therefore forms a background which show spatial fluctuations, i.e. contribute to the confusion noise of the sky background. Since the detection of many sources in the CIB is an important goal for space infrared telescopes (for Herschel as well), it is important to emphasis again, that the actual confusion noise may be different for an 'unbiased survey' (detection of as many so far unknown sources as possible) or for the photometric accuracy of a single target. For deep surveys clearly detected sources do not contribute to the background any more. Since in realistic source counts fainter sources are more numerous only sources around or below a certain flux level contribute to the confusion noise.

Chapter 6. Importance of sky confusion noise for the Herschel Space Telescope

As discussed in the chapters above, there are two main components, which has a notable conttribution to the confusion noise for Herschel/PACS and SPIRE photometric observations. These are the extragalactic background (specifically the cosmic infrared background) and the thermal emission of the interstellar medium in the Galaxy. This latter one consits of two main components: the dust related to the mostly molecular gas, concentraed around the Galactic midplane, and a more extended emission, related the dust in weak neutral hydrogen clouds, the Galactic cirrus emission. Confusion noise due to other components (zodiacal light, asteroids) has proved to be negligible for the Herschel mission (see above) therefore has not been considered hereafter.



The relative strength of confusion noise component for the PACS red (175µm) photometric band in equatorial (FK5) coordinates. Three kind of regions are discriminated according to the dominant source of confusion noise: *deep blue*, CIB dominated; *medium blue*, cirrus and CIB are in the same order; *light blue*, cirrus (ISM) dominated. The light blue region closely follow the shape of the Galactic plane. Overlays represent the ISO pointing density of a specific 'cell' in the sky (0.5°x0.5°). Blue dots mark single pointing, while red spots are the most frequetly visited positions.

Figure 6.1. Relative strength of the major confusion noise components for PACS

In the figure above we demonstrate the relative strength of the two main components in the sky for the PACS red band. The CIB is the dominant component for high Galactic latitudes. The expected contribution to confusion noise in the PACS blue bands is ~0.1mJy or below, while it is at in the 1mJy level for the PACS red filter (see e.g. Jeong et al. 2006). SPIRE will have to face about 6.7mJy, 9.6mJy and 7.7mJy CIB 1σ confusion noise values in the 250, 350 and 500µm bands, respectively. In these regions the contribution of the cirrus emission is negligible. However, closer to the Galactic plane the cirrus compnent becomes dominant. For medium surface brightness regions the cirrus contribution can reach confusion noise values in the order of 1mJy in the PACS blue bands and ~10mJy in the PACS red band. For the SPIRE filters the cirrus confusion noise remains in the ~10mJy order for medium surface brightness regions, since the intensifying confusion noise by the increasing wavelength is compensated by the declining SED of the cirrus, compared to the FIR.

Chapter 7. The Herschel Confusion Noise Estimator

7.1. General comments

The Herschel Confusion Noise Estimator (HCNE) is described in detail in the document "Requirements for the integration of the Herschel Confusion Noise Estimator Prototype", version 1 (latest version: 2006 April 24). Below we summarize the science related issues of the HCNE only.

As discussed above, there are only two components of the sky background that give notable contribution for the confusion noise at the photometric bands of Herschel/PACS and SPIRE. These are the thermal emission of the interstellar medium (Galactic cirrus) and the extragalactic background (namely the cosmic infrared background).

Due to their weakness, other sources, e.g. the Zodiacal Light and asteroid population in the Mail Belt, are not considered as contributors to the confusion noise. However, the HCNE code have been designed in a way, that any component which can be described by a the functional form of the multiplication of two functions ($L(\lambda)\times S(\alpha,\delta)$) can be easiliy included in the code at a later stage, since dummy functions of this kind are left in the code. Here $L(\lambda)$ is a purely wavelength dependent function and $S(\alpha,\delta)$ is a purely coordinate-depedent one.

Since the HCNE is used to give estimates for the detection of single stellar sources, it uses the 'single target' or 'full' interpretation of the confusion noise, i.e. the effect of detected sources are not taken into account separetely.

7.2. Cosmic infrared background:

In the current version of HCNE only the isotropic component of the cosmic infrared background is considered. This means, that using the functional form above $S(\alpha,\delta)_{CIB}$=const. for any α and δ, and the $L(\lambda)$ function is the 'spectral energy distribution of the confusion noise'.

In the present version the cosmic infrared background and their fluctuations are calculated using the model of infrared galaxies at Institut d'Astrophysique Spatiale. The model is described in details in Lagache et al. (2003) and Lagache et al. (2004), and data products related to the model are publicly available at the URL: http://www.ias.u-psud.fr/irgalaxies/. The immediate output of the model at a specific wavelength is a fluctuation power (P, units of Jy^2sr^{-1}), which is then converted to confusion noise amplitude (N) using the effective solid angles (Ω) of the detector pixels: $N = (P\times\Omega)^{1/2}$

In later versions of HCNE the effect of galaxy clustering and its effect to the confusion noise may be considered. Recent results show that galaxy clustering increases the source confusion by ~10% for the Herschel mission (Negrello et al. 2004).

7.3. Galactic cirrus

Mainly due to its simplicity over the method used by Jeong et al. (2005), we used the method described in Kiss et al. (2005) to account for the confusion noise due to Galactic cirrus -- or in general due to the thermal emission of the interstellar medium (see Sect. 4). To simplify the technical realization of this component in HCNE, we used pre-calculated confusion noise values in a double parameter lookup table. The two independent variables are the wavelength λ and the surface brightness $I\lambda$. The structure of the emitting medium is considered through the spectral index α (see Sect. 4) and is wired into the lookup tables through its λ and $I\lambda$ dependence, i.e. in the calculation of the cirrus confusion noise $N_{cirr}(\lambda,I\lambda)$ the specific $\alpha(\lambda,I\lambda)$ is applied.

7.4. Measurement configuration

Measurement configurations are important in calculating the confusion noise values, each measurement configuration has a different confusion noise level, even when using the same instrument/filter setup (see Kiss et al. 2005). In HCNE the confusion noise values of the different components (CIB and cirrus) are stored for a given 'reference' configuration only. Actual confusion noise values are calculated using the confusion noise values of this reference configuration, and coefficients relevant for the current configuration. These coefficients are calculated in advance, and stored in lookup tables in HCNE. The coefficients themselves depend on the basic parameters of the observing configuration as set in the HSPOT observation designing tool. The relevant HSPOT parameters are listed in RD2.

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