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A CODE TO CONVERT EXTENDED SOURCE CATALOGS INTO HEALPIX MAPS

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SUMMARY - We present here a code to convert a catalog of extended sources into a HEALPIx map at desired resolution with or without including the convolution with an instrumental beam of given $FWHM$. In the former case, the code takes into account not only the angular extent of the source but also the beamwidth. The code is tested and applied to an extensive catalog of Galactic HII regions. Examples of maps obtained at frequencies relevant for CMB experiment are provided.

1 Introduction

High-resolution and large-volume CMB data sets, such as WMAP and PLANCK products, represent a big challenge for data analysis and require specific tools for being handled.The Hierarchical Equal Area and Iso-Latitude Pixelization of the sphere (HEALPix, Górski et al. 1999) meets the specific requirements of these kind of data sets and, for this reason, it is widely used within the CMB community. In this framework, great efforts have been devoted to for diffuse emissions, i.e. the CMB signal and diffuse foregrounds (synchrotron, free-free and dust) and point-like sources, Galactic or extragalactic. In particular, built-in routines are not designed for sources which are neither point-like nor extended over the entire sky but shown typical sizes or the same order of the pixel or beamwidth size. The work that here we present is focussed on this kind of sources.
The report is organized as following. Sect. 2 describes the procedure used for building maps of extended sources starting from the corresponding catalog; Sect. 3 presents the application of the code to the scientific case of Galactic HII regions for which we provide examples of the derived maps; in Sect. 4 we summarize the main results and conclusions. The code usage is described in Appendix A.

2 Method

In order to convert a catalog of extended sources into a HEALPix map, two elements have to be considered:

1. the angular extension of the extended source;
2. the resolution parameter of the HEALPix map.

For simplicity, the code does not include possible asymmetries of the source brigthness distribution with respect to a symmetric Gaussian profile about the source centre direction. Analogously, possible main beam distortions and the details of experiment scanning strategies are neglected, as well as the frequency dependence of the source and of the instrument response inside the bandwidth. Of course, these aspects, although not critical, may be not negligible in realistic cases. On the other hand, their accurate inclusion requires to specify the details of the considered experiments, both of those performed to generate the original database and of those for which the production of code output map is devoted, and makes non general the catalog to map conversion.

It is common use to estimate the angular extension of the source in terms of the full width half maximum ($FWHM_{sour}$) of the Gaussian profile which approximates the brightness distribution of the source. On the other hand, the resolution parameter of a HEALPix map, N_{side}, represents the number of divisions along the side of a base-resolution pixel. In particular, $N_{side} = 2^N$ where $N \in [0,13]$ and the total number of pixels of a map is $n_{px} = 12 \times N_{side}^2$. Given these two parameters, the code works according to these guidelines:

1. the solid angle subtended by the source, assuming a Gaussian profile, is computed as:

$$\Omega_{sour} = \pi r_{eff}^2 \tag{1}$$

   where the *effective* 3σ radius, r_{eff}, is expressed in in rad and it is defined as:

$$r_{eff} = \left(\frac{FWHM_{sour}}{2}\right)\frac{3}{\sqrt{2\log 2}}\,; \tag{2}$$

2. the solid angle subtended by the pixel is computed according to the relation:

$$\Omega_{px} = \frac{4\pi}{n_{px}}\,; \tag{3}$$

3. if Ω_{sour} is $\leq 1.5\times\Omega_{px}$ then: the coordinates of the source (Galactic, Celestial or Ecliptic) are associated to a pixel map and the flux (converted into antenna temperature) of the source is entirely assigned to this pixel;

4. if, on the contrary, Ω_{sour} is $> 1.5\times\ \Omega_{px}$ then: the coordinates of the source are associated to a pixel map through cosine vectors; all the pixels within the source *effective* radius, r_{eff}, are selected; each of these pixels is assigned a fraction of the total source flux (converted into antenna temperature) weighted by the angular distance between the considered pixel and the center of the source as given by the source coordinates.

These simple lines allow to project a catalog of extended sources into the HEALPix scheme without losing information on the flux and angular size of the source. As well as realizing the projection, the code has been designed also to consider the case in which the extended sources are observed by an instrument with a beam of a given angular resolution. In this case, the convolution of the sources with the beam is performed in real space. By adopting a Gaussian profile for the beam, we denote with $FWHM_{beam}$ its full width at half maximum. The procedure for obtaining a convolved map is described hereafter:

1. for each i-th pixel of the map obtained before, all the j-th pixels within an angular radius corresponding to 5σ of the $FWHM_{beam}$ are selected;
2. for each of these j-th selected pixels, the flux (in antenna temperature) is weighted by the Gaussian profile of the beam given its angular distance from the initial i-th pixel;
3. if the weighted flux (in antenna temperature) in the j-th pixel is larger than the instrumental noise per pixel, the flux is assigned to the i-th pixel in the convolved map.

It is important to emphasize that in order to optimize the quality of the code results and, in particular, to avoid to lose information on the source brightness distribution possibly accessible to the considered experiment, it is recommended the use a value of N_{side} which allows a correct sampling of the considered extended sources, taking into account their average angular extent.

3 Case study

The application of the code to HII regions is also relevant from the astrophysical point of view: these sources are in fact particularly bright free-free emitters; as a consequence they contribute to the so-called Galactic foregrounds, i.e. the radiation produced by the Galaxy at centimeter wavelength and which needs to be accurately subtracted from CMB maps. As well as being a contaminant of the CMB signal, HII regions may also represent a source of straylight, that is the unwanted radiation which gets into the main beam from the sidelobes (Burigana et al. 2003). Taking into account these various effects, the conversion of the HII regions catalog into the HEALPix projection is useful not only to test the code but, in view of satellite CMB measurements such as the on-going WMAP and the 2007-planned PLANCK, it is useful to estimate the impact of these sources on the overall experiment performance.
We have applied the code to the case of a radio catalog of Galactic HII regions (Paladini et al. 2003). The cataloged sources have an average angular diameter of $6'$ therefore being good candidates for testing the code. The catalog contains a significant number (1442) of sources which are, for the vast majority, distributed along the Galactic Plane in regions of overdensity. The Paladini et al. catalog consists of a Master Catalog (which contains the original information on flux and angular diameter as well as on other relevant astrophysical quantities) and of a Synthetic Catalog (in which all the information of the Master Catalog for each source is summarized). In the Synthetic Catalog fluxes are quoted at one single frequency, namely 2.7 GHz. For the present application, we have made use of the Synthetic Catalog.
We have procedeed along the following lines:

1. we have converted the 2.7 GHz catalog into HEALPix map;
2. we have produced convolved maps of the catalog having in mind the typical angular resolution of satellite missions such as WMAP and PLANCK and extrapolating the HII regions signal at frequencies relevant for these experiments.

In accomplishing the first step, one has to pay attention, as mentioned in the previous section, to the choice of N_{side}. We have chosen N_{side}=1024 which corresponds to a pixel size of

the order of $\sim 3'$. This value is close to the average angular diameter of the cataloged HII regions therefore providing a sampling of the sources good enough for WMAp and PLANCK. We show in Fig. 1 the resulting 2.7 GHz map.
We than assume that the cataloged HII regions are observed by a high-resolution, high-sensitivity CMB-dedicated instrument, such as WMAP or PLANCK operating, at two nominal frequencies, 30 and 70 GHz, with angular resolution of $\sim$ 30 and 10 arcmin, respectively. In both cases, in order to obtain convolved HEALPix maps, we first extrapolate the catalog fluxes to the given frequency and then perform the convolution of the sources with a Gaussian beam with $FWHM_{beam}$ equal to the instrumental angular resolution. The spectral index $\alpha = -0.1$, with $S \propto \nu^{\alpha}$, has been used for flux extrapolation, being this value typical of free-free emission in the optically thin regime. Nominal noise per pixel of the order of a few μK are used as a threshold and convolved pixels are selected with respect to it. The final convolved maps are illustrated in Fig. 2 (30 GHz - $FWHM = 33.6'$) and Fig. 3 (70 GHz - $FWHM = 13'$).

4 Conclusions

We have implemented a simple code which converts a catalog of extended sources into a HEALPix map. By optimizing the choice of the parameter N_{side}, it is possible to realize the best sampling of the sources without losing information of the source flux. We have also implemented a code which performs the convolution of the cataloged sources with and instrumental beam at a given frequency. The convolution is made in real space by considering only the relevant pixels of the map. The code takes also into account the noise per pixel of the considered instrument so that the final convolved map is a selection of the convolved pixels with respect to the instrumental threshold.

Acknowledgements. Some of the results in this paper have been derived using the HEALPix (Gòrski et al. 1999).

References

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A The code

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The tool is provided as a set of subroutines plus a simple (driver) main program to call them. Current implementation assumes the input catalog in ASCII file and produces the output binary files with pixel number and corresponding signal only for the limited number of pixels with non negligible signal.

- **CAT_TO_MAP**.f90

This routine convert a catalog of extended sources into a HEALPix map.

FORMAT
call cat_to_map(filename_cat,n_sou,nu_GHz,coord_type,n_side,n_pix,map)

ARGUMENTS

name	description
filename_cat	the input catalog filename
n_sou	number of cataloged sources
nu_GHz	frequency of extrapolation for output map
coord_type	input source coordinates (1: celestial ; 2: Galactic ; 3: ecliptic)
n_side	resolution of the output HEALPix map
n_pix	number of pixels in the output HEALPix map
map	output HEALPix map

- **SMOOTH_REAL**.f90

This routine converts a catalog of extended sources convolved with an instrumental beam of given resolution into a HEALPix map.

FORMAT
call smooth_real(n_side,n_pix,map,$FWHM$_arcmin,n_sigma,smooth_map)

ARGUMENTS

name	description
n_side	resolution of the output HEALPix map
n_pix	number of pixels in the output HEALPix map
map	input HEALPix map
$FWHM$_arcmin	beam resolution of observing instrument (arcmin units)
n_sigma	sigma cutoff of Gaussian source profile
smooth_map	output convolved HEALPix map

- **WRITE_NONULL_PIX_TMKA**.f90

This routine writes a binary file containing the HEALPix map of the extended cataloged sources.

FORMAT
call write_nonull_pix_TmKa(n_side,n_pix,map,file_nonull_map)

ARGUMENTS

name	description
n_side	resolution of the output HEALPix map
n_pix	number of pixels in the output HEALPix map
map	input HEALPix map
file_nonull_map	output binary file containing HEALPix map

- **WRITE_NONULL_PIX_TMKA_SMOOTH**.f90

This routine writes a binary file containing the convolved HEALPix map of the extended cataloged sources.

FORMAT
call write_nonull_pix_TmKa_smooth(n_side,n_pix,smooth_map,wn_per_pix_mKa,n_threshold,
file_nonull_smooth_map)

ARGUMENTS

name	description

n_side	resolution of the output HEALPix map
n_pix	number of pixels in the output HEALPix map
smooth_map	input HEALPix convolved map
wn_per_pix_mKa	instrumental white noise per pixel (mK units)
n_threshold	output convolved map threshold factor
file_nonull_smooth_map	output binary file containing HEALPix convolved map

MODULES & ROUTINES

This section lists the external modules and routines used by cat_to_map; smooth_real; write_nonull_pix_TmKa; write_nonull_pix_TmKa_smooth.

module name	routine or function name
- HEALPix modules and routines	
healpix_types	–
wrap_fits	–
fitstools	–
pix_tools	pix2vec_ring
	getdisc_ring

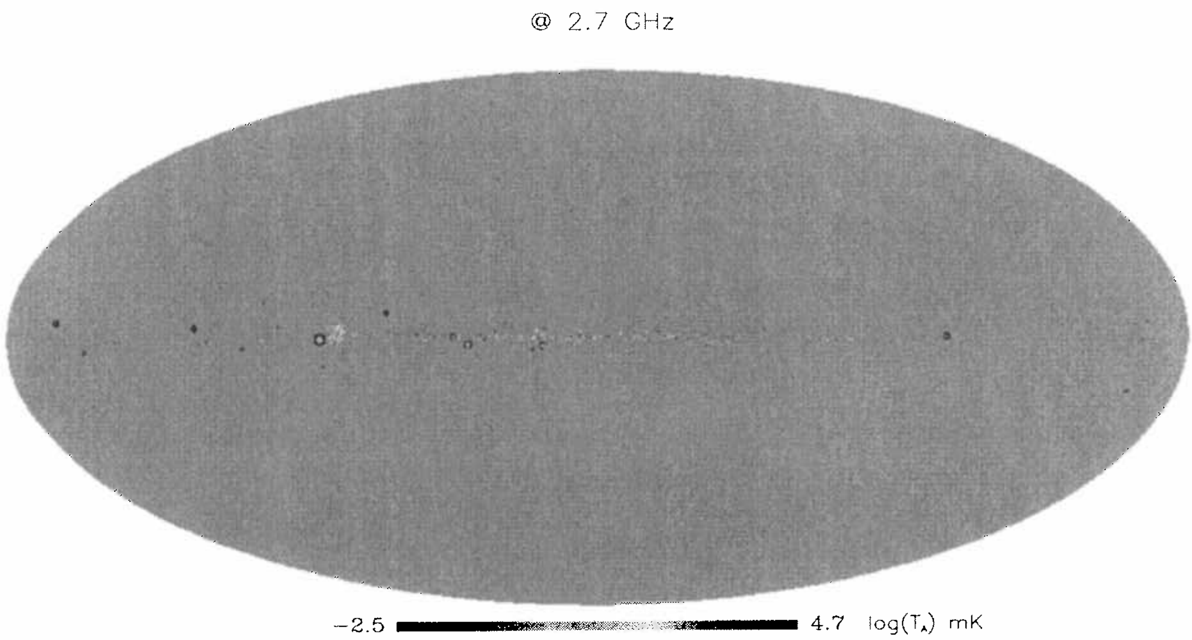

Figure 1: HII region template at 2.7 GHz in HEALPix format and $N_{side} = 1024$.

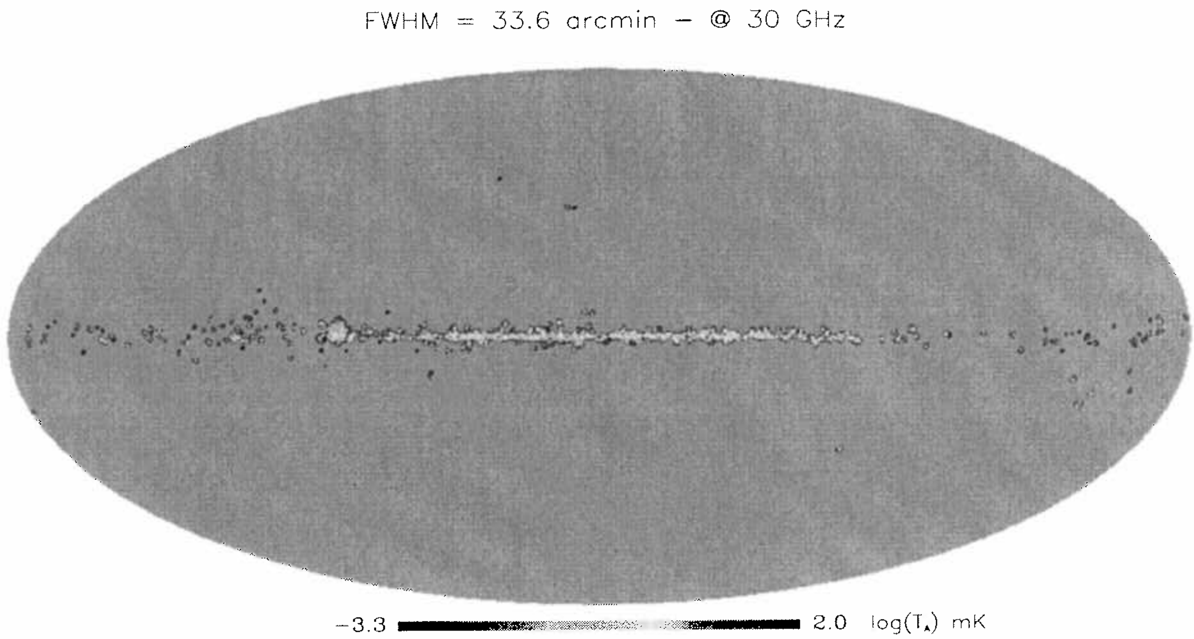

Figure 2: HII region template at 30 GHz, convolved with a $33.6' - FWHM$ beam. The map is in HEALPix format and $N_{side} = 1024$.

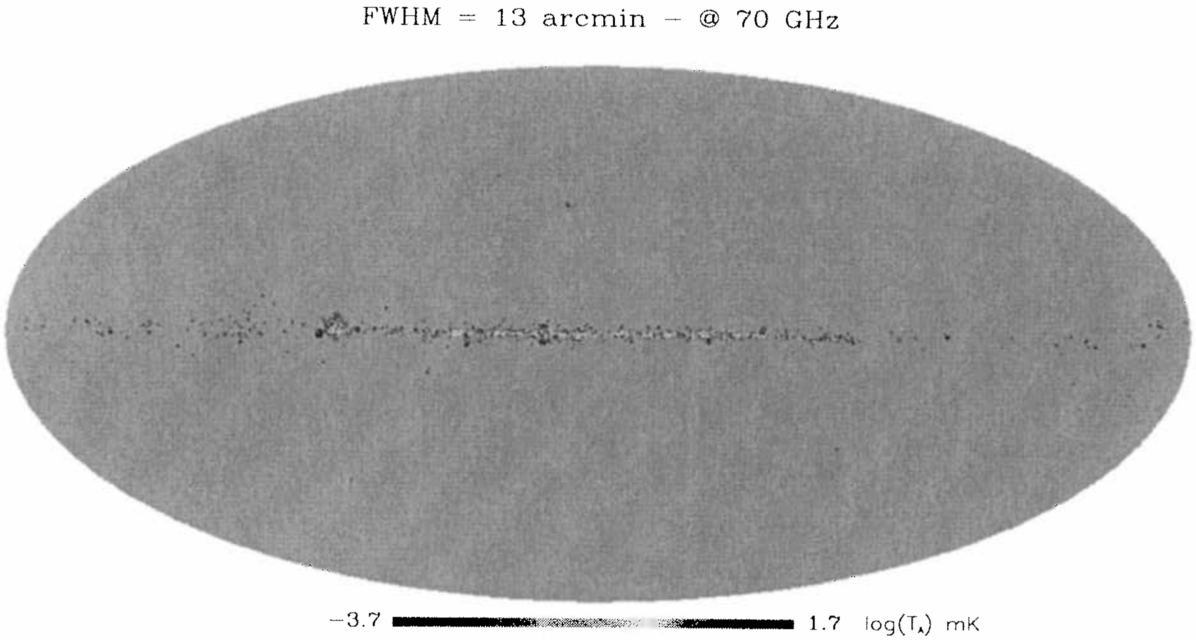

Figure 3: HII region template at 70 GHz, convolved with a $13' - FWHM$ beam. The map is in HEALPix format and $N_{side} = 1024$.