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PERSPECTIVES OF OBSERVATIONS OF GALACTIC HII REGIONS WITH MILLIMETER TELESCOPES

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SUMMARY – HII regions are very important radio astrophysical sources within our Galaxy. Despite their relevance within the astrophysical scenario, the number of Galactic HII regions observed at millimeter wavelengths is quite small. Recently, Paladini et al. (2002) have produced a Catalog that collect all the available data on diffuse and compact Galactic HII regions (Master Catalog) and extract a Synthetic Catalog of source diameters and fluxes at 2.7 GHz. In this note, we exploit the richness of this Catalog to investigate the possibility of performing useful observations of Galactic HII regions with millimeter telescopes with relatively low sensitivity, moderate angular resolution, and quite poor accuracy in the "a priori" telescope pointing capability. For sake of concreteness we apply this method to the typical performances of the Telescopio a Onde Millimetriche (TOM), by the IR group at IASF/CNR - Sezione di Bologna. We first discuss the sensitivity to measures of point bright sources of millimeter telescopes originally designed to use the sky scan approach to measure sky temperature fluctuations, then include in the Signal to Noise (S/N) ratio evaluation the effect of the convolution with the antenna beam pattern and of the most important Galactic HII region observational property, their angular size and their quite uniform brightness distribution on their angular extent, and finally exploit the Catalog by Paladini et al. (2002) to derive the distributions of S/N for the considered sources according to the considered instrument sensitivity levels (30, 10, 3 mK per second of integration). We find that in the case of the worst sensitivity level there is no room for fruitful observation campaigns, unless the number of available nights is very large. On the contrary, the other two cases are quite interesting: a number of sources from several tens to few hundreds can be in principle observed in reasonable time with a good S/N ratio. This kind of observations can provide a scientific improvement to our knowledge of Galactic HII regions, since the quite poor amount of data available at millimeter wavelengths. We finally discuss some technological and observational requirements necessary to successfully perform this kind of observations in the context of the TOM project.

1 Introduction

HII regions are very important radio astrophysical sources within our Galaxy. They not only provide information about the early stages of stellar formation but they also represent a unique tool to investigate the Galactic spiral structure. Moreover, their radio emission, not affected by dust extinction, is particularly powerful and enable us to probe the far sides of the Galactic plane which, otherwise, would be heavily obscured.

At infrared/sub-millimetric the emission toward Galactic HII regions is dominated by the thermal (and possibly non-thermal) emission of dust grains associated to the HII regions, while the transition from the free-free dominated spectral region to the dust emission dominated spectral region is expected to be at millimetric wavelengths. Despite their relevance within the astrophysical scenario, the number of Galactic HII regions observed at millimeter wavelengths is quite small and do not exist exhaustive observational studies at these wavelengths.

Since the high quality data from recent ballon-borne cosmic microwave background (CMB) anisotropy experiments at millimeter wavelengths (de Bernardis et al. 2000, Hanany et al. 2000) and those expected in the next future from the MAP satellite by NASA from 1.5 cm to 3 mm (Bennett et al. 1996), several ground millimeter telescopes with relatively lower performances, originally designed to measure CMB and diffuse foreground anisotropies, can be in principle usefully employed to observe relatively bright discrete sources, before the very high quality data at millimeter and sub-millimeter wavelengths expected for the 2007-2008 from the Low Frequency Instrument (Mandolesi et al. 1998a) and the High Frequency Instrument (Puget et al. 1998) on-board the PLANCK satellite by ESA. Galactic HII regions seem to be the most favourable class of objectes to be investigated.

Recently, Paladini et al. (2002) have collected all the available data on diffuse and compact Galactic HII regions, according to the classification by Lockman et al. (1996) (ultra-compact and extremely extended objects, less relevant for our purposes, are not included in their Master Catalog), from radio frequencies to centimetric wavelengths.

In this note, we exploit the richness of this Catalog to investigate the possibility of performing useful observations of Galactic HII regions with millimeter telescopes with relatively low sensitivity (from few mK to few tens of mK per second of integration), moderate angular resolution ($10'$–$20'$), and quite poor accuracy ($\sim$ degree) in the "a priori" telescope pointing capability (i.e. the accuracy of the telescope pointing in a given direction; clearly, the analysis of the data taken during the sky observation will allow a much better pointing accuracy reconstruction from the analysis of bright source positions). Although our approach is general and potentially applicable to any ground experiment, for sake of concreteness we adopt here in some numerical estimates the typical performances of the Telescopio a Onde Millimetriche (TOM) by the IR group at IASF/CNR - Sezione di Bologna.

In Table 1 we report the fundamental information on the 24 previously published lists and catalogs collected in the Master Catalog by Paladini et al. (2002), consisting of 1442 sources, that will be exploited in this report.

In Sect. 2 we discuss the sensitivity to measures of point bright sources of millimeter telescopes originally designed to use the sky scan approach to measure sky temperature fluctuations. In Sect. 3 we include in the Signal to Noise (S/N) ratio evaluation the effect of the convolution with the antenna beam pattern and of the most important Galactic HII region observational property: their angular size and their quite uniform brightness distribution on their angular extent. In Sect. 4 we exploit the Catalog by Paladini et al. (2002) to derive the distributions of S/N for the considered sources according to the considered observation sensitivity levels. Finally, we draw our main conclusions in Sect. 5.

Table 1: List of the references (in alphabetical order) used for the Master Catalog compilation by Paladini et al. (2002). Listed l_{min} and l_{max} provide the longitude range spanned by each survey. Tipically, the range in latitude is $|b| \leq 2^0 - 4^0$.
† Number of sources after subtraction of nonthermal objects; (a) the list of sources is retrieved by the intersection with the radio recombination line survey by Lockman et al. (1989); (b) Parkes survey; (c) Effelberg 100-m survey; (d) Cygnus X; (e) nonuniform sky coverage; (f) Green Bank and Parkes-MIT-NRAO surveys cover almost the whole sky: HII regions have been identified from either optical or radio recombination line surveys along the disk.

Reference	l_{min}	l_{max}	ν *(GHz)*	HPBW (′)	*Number*† *of sources*
Altenhoff et al. (1970)	335^0	75^0	1.4/2.7/5	10	325
Altenhoff et al. (1979)$^{(a)}$	2^0	60^0	5	2.6	265
Beard (1966)$^{(b)}$	331^0	333^0	2.7	7.4	13
Beard & Kerr (1969)$^{(b)}$	27^0	38^0	2.7	7.4	34
Beard et al. (1969)$^{(b)}$	345^0	5^0	2.7	7.4	72
Berlin et al. (1985)	4^0	10^0	3.9	0.8×18.3	45
Caswell & Haynes (1987)	190^0	40^0	5	4.2	308
Day et al. (1969)$^{(b)}$	307^0	330^0	2.7	8.2	109
Day et al. (1970)$^{(b)}$	37^0	47^0	2.7	8.2	48
Downes et al. (1980)	357^0	60^0	5	2.6	169
Felli & Churchwell (1972)	(*e*)	(*e*)	1.4	10	80
Fürst et al. (1987)$^{(c)}$	(*e*)	(*e*)	2.7	4.27	7
Goss & Day (1970)$^{(b)}$	6^0	26^0	2.7	8	85
Kuchar & Clark (1997)	(*f*)	(*f*)	4.8	3.1/4.2	760
Mezger & Henderson (1967)	(*e*)	(*e*)	5	6.3	17
Reich et al. (1986)$^{(c)}$	(*e*)	(*e*)	2.7	4.27	5
Reifenstein et al. (1970)	348^0	80^0	5	6.5	105
Thomas & Day (1969a)$^{(b)}$	288^0	307^0	2.7	8.2	39
Thomas & Day (1969b)$^{(b)}$	334^0	345^0	2.7	8.2	29
Wendker (1970)$^{(d)}$	76^0	84^0	2.7	11	77
Wilson et al. (1970)	282^0	346^0	5	4	132
Wink et al. (1982)	(*e*)	(*e*)	5/15/86	2.6/1/1.3	112
Wink et al. (1983)	359^0	50^0	14.7	1	84

2 Exploiting millimeter telescope performances

Let $rms_{1s,a}$ the rms sensitivity in terms of antenna temperature of the considered experiment per second of integration. For a point source observed exactly at the beam centre, the corresponding sensitivity per second of integration in terms of flux is:

$$(rms_{1s,f}/\mathrm{Jy}) = 2.95 \times 10^{-3} (\mathrm{FWHM}/\mathrm{arcmin})^2 (\nu/GHz)^2 (rms_{1s,a}/\mathrm{K}) \,, \tag{1}$$

where FWHM is the beam Full Width Half Maximum and ν is the observation frequency (Burigana 2000a).

Of course, the sensitivity for a given integration time, τ, scales as $1/\sqrt{\tau}$. For scan experiments, this sensitivity is typically given considering the comparison between two signals: one with the beam centred on the sources, the other with the beam in the adjacent pointing in the sky, i.e. for a global telescope angular scan of $\simeq$ 2FWHM. On the other hand, the limited pointing accuracy implies that not the whole integration time of a given exposure is taken on the considered source.

Let $\Delta\theta$ the telescope a-priori pointing accuracy according to the following definition: when the observer wants to point the telescope at a given direction, $\vec{p}$, the real telescope pointing direction is around $\vec{p}$ within a typical uncertainty box with an angular side of $2\Delta\theta$.

Millimeter telescopes designed to measure CMB and foreground anisotropies, typically scan the sky through oscillations of the telescope pointing parallel to the ground, in order to have the same air mass for all the telescope pointings. They use the Earth rotation to observe different sky regions.

For simplicity, we derive in this section S/N ratios under the assumption that a beam FWHM transit time is the useful integration time to integrate over the source signal, observed with the maximum of the beam response. Corrections to proper include the beam response and the source extent will be discussed in the next section.

To be sure to observe the considered source, the amplitude of the horizontal scan oscillation has to be at least of $\simeq 2\Delta\theta$. Therefore, the integration time useful to measure the source flux is given by the global integration time multiplied by a *first correction factor*:

$$f_1 \simeq 2\mathrm{FWHM}/2\Delta\theta \,. \tag{2}$$

Let us consider an observatory latitude of $\simeq 28°$, as in the case of the TOM experiments at the Canarias. Ground observations have to be carried out by pointing at relatively small angles ($\lesssim 45°$) from the observation site zenith, in order to avoid a significant air mass contamination. The apparent source angular velocity on the celestial sphere, $\Delta h/\Delta t$, depends on the source angular distance from the Earth rotation axis:

$$\Delta h/\Delta t \simeq 15\mathrm{arcmin} \times \sin c/60\mathrm{sec} \,, \tag{3}$$

where c is the source celestial colatitude; under the above assumptions, the value of $\Delta h/\Delta t$ is from 4.5arcmin/60sec to 15arcmin/60sec, the minimum and maximum value referring respectively to a source at $\simeq 45°$ (from the zenith from the zenith to the North Pole) and to a source at 90° from the Earth rotation axis.

The minimum global integration time of an exposure to be sure to observe the considered source is again related to the pointing accuracy and is given by:

$$\tau_{exp} \simeq 2\Delta\theta/(\Delta h/\Delta t) \,. \tag{4}$$

Only a fraction of the exposure integration time is useful to measure the source flux; this is taken into account by introducing a *second correction factor*, given by:

$$f_2 \simeq 2\mathrm{FWHM}/[\tau_{exp} \times (\Delta h/\Delta t)] \,. \tag{5}$$

Considering the fractions f_1 and f_2, that substantially give the fraction of integration time on the source because of the telescope scans and the Earth rotation respectively, we have that the integration time on the source corresponding to the exposure time τ_{exp} is given by:

$$\tau_{sou} \simeq f_1 f_2 \tau_{exp} \simeq \tau_{exp} \times [2\mathrm{FWHM}/2\Delta\theta] \times 2\mathrm{FWHM}/[\tau_{exp} \times (\Delta h/\Delta t)] \,. \tag{6}$$

As obvious, this time does not depend on τ_{exp} but only on the beamwidth, the pointing accuracy and the source position.

For sake of illustration, let consider a source at small angles from the zenith, at about 60° from the North Pole, where the atmosphere contamination is minimum and assume $\Delta\theta \simeq 1°$ and FWHM$\simeq$ 13arcmin. In this case $\Delta h/\Delta t \simeq 13\mathrm{arcmin}/60\mathrm{sec}$, $\tau_{exp} \simeq 9.2\mathrm{min}$ and $\tau_{sou} \simeq 26\mathrm{sec}$.

Summing up, we have that to be sure of observing the considered source inside an angular box with solid angle of about $(2\Delta\theta)^2$, we have to consider exposure times of about 10 min, while the corresponding integration time on the source is of about 0.5 min. Fortunately, at least for some sky regions rich of Galactic HII regions, with a single exposure it is possible to observe several sources.

3 Exploiting beam shape and source extent

The first step to evaluate the S/N ratio for observation of Galactic HII regions at millimeter wavelengths is to extrapolate their fluxes from frequencies of few GHz, where observations are currently available. For this purpose, we exploit the Synthetic Catalog of fluxes and diameters at 2.7 GHz derived by Paladini et al. (2002) by extrapolating the 2.7 GHz fluxes with a power law $F_\nu \propto \nu^{-0.1}$, typical of the free-free emission in the optical thin regime.

The sensitivity estimates reported in the previous section are based on the assumption of point-like source and of telescope pointing toward the source centre for the whole integration time, i.e. under the assumption that the beam effective response, R_{eff}, normalized to the maximum, is always unit.

In reality, the considered, relatively bright, Galactic HII regions are extended sources. For a detailed prediction of the observed flux we need in principle to know the brightness distribution and to convolve it with the beam shape response. Of course this is impossible. On the other hand, we can improve the previous analysis by approximately taking into account the beam shape and exploiting the available information of source diameter, d, under the simple, albeit quite realistic, assumption of uniform brightness distribution.

For simplicity, we distinguish three different cases.

i) "Compact" sources (sources with $d \lesssim$ FWHM/3).

In this case, when the considered source transits on the beam, we have that the source is observed at an angular distance from the beam centre, $\vartheta \simeq 0°$, for about 1/8 of the integration time, while for about 7/8 of the integration time it is observed at $\vartheta \simeq$ FWHM/3. Assuming a symmetric Gaussian beam, we have then $R_{eff} \sim 0.75$. The information on source flux when the source falls out of beam (FWHM) is too poor with respect to that obtained when the source falls in the beam, and can be neglected.

We then multiply the source flux extrapolated to millimeter wavelengths by the factor $R_{eff} \sim 0.75$ and assume the sensitivity as derived in the previous section.

ii) "Intermediate" sources (sources with FWHM/3 $\lesssim d \lesssim$ FWHM).

Let consider as a reference the case of a source with $d \sim (2/3)$FWHM.

In this case, when the source falls in the inner main beam region (i.e. it is entirely within the beam FWHM), the contributions from the central beam regions are relatively larger than in the previous case, and we find $R_{eff} \sim 0.85$.

On the other hand, for relatively extended sources the signal is significant also when the source centre falls in the outer main beam regions, at an angular distance $\vartheta \sim$ FWHM/2. In this case $R_{eff} \sim 0.4$ but the integration time with the source in this positions is about 4–5 times larger than that in which the source falls completely into the beam (FWHM). In terms of S/N ratio the two contributions are similar. We then multiply the source flux extrapolated to millimeter wavelengths by the factor $R_{eff} \sim 0.85$ and assume a rms noise $\sim \sqrt{2}$ times smaller than that evaluated in the previous section.

iii) "Quite extended" sources (sources with $d \gtrsim$ FWHM).

Let consider as a reference the case of a source with $d \sim 2$FWHM.

In this case, within the beam FWHM, where $R_{eff} \sim 0.8$, it falls only about 1/4 of the source flux. On the other hand, the observed source signal is essentially the same for a solid angle in the sky which is about 4–5 times the beam solid angle defined by the FWHM.

We then multiply the source flux extrapolated to millimeter wavelengths by the factor $R_{eff} \sim 0.2$ and assume a rms noise ~ 2 times smaller than that evaluated in the previous section.

4 Exploiting the Catalog of Galactic HII regions

The results obtained in the previous sections can be applied to the Catalog of Galactic HII regions by Paladini et al. (2002) to estimate the S/N ratios for measurements of source flux with millimeter telescopes.

We assume here for sake of illustrations the typical instrument performances forseen for the TOM project.

According to preliminary measurements based on the Moon transit (Gardini 2002) that are in agreement with the results based on optical considerations, the beam FWHM is respectively of about 10 and 17 arcmin at the two channels at 1.1 and 2.1 mm.

For numerical estimates we consider here $\nu \simeq 200$ GHz and FWHM$\simeq 13$ arcmin.

We adopt an a-priori telescope pointing accuracy of about 1 deg and source transits quite close to the observatory zenith, as discussed in Sect. 2.

We consider the S/N ratios as derived by considering a *single exposure* with about 9 min of integration (i.e. of about 26 sec of integration on the source for the reference case of a point source) and a *one night* observation, i.e. the collection of 18 exposures, corresponding to three exposures per hour for six hours of observations.

By considering three different intrument sensitivity levels (30, 10, 3 mK per second of integration) we compute the number of sources per bin of S/N ratio and the number of sources with a S/N ratio better than a certain value (i.e., essentially, the distribution function and the cumulative distribution function of the S/N ratios). More explicitely, we divided the interval $[\log(\min(S/N)), \log(\min(S/N))]$ of each case in 100 bins equispaced in log(S/N). Of course, our estimates are conservative, since the dust emission toward the sources, not included in this analysis, may be relevant at millimetric wavelengths.

The results are shown in Figs. 1, 2, and 3 respectively for an instrument sensitivity of 30, 10, 3 mK per second of integration. The dotted lines refer to the case of a *single exposure* while the dashed lines refer to the case of a *one night* observation; for both cases, the lower (thin) lines refer to the distribution functions and the upper (thick) lines to the cumulative distribution functions.

5 Discussion and conclusion

As evident from Figs. 1, 2, and 3, in the case of the worst sensitivity there is no room for fruitful observation campaigns, unless the number of available nights is very large or the dust emission close to the sources is much larger than the free-free emission.

On the contrary, we find that the other two cases are quite interesting: a number of sources from several tens to few hundreds can be in principle observed in reasonable time with a good S/N ratio. This kind of observations can provide a scientific improvement to our knowledge of Galactic HII regions, since the quite poor amount of data available at millimeter wavelengths. Of course, it will be very useful to combine measures at millimetric wavelengths with measures at centimetric wavelengths, that can be planned in the future by taking advantage of the recently improvements at these frequencies of available radiotelescopes, and with sub-millimetric and infrared observations.

We discuss here below some technological and observational requirements necessary to successfully perform this kind of observations in the context of the TOM project.

a) **Sensitivity**. Of course, the first fundamental step is to ensure a good instrument sensitivity. Although a sensitivity of ~ 3 mK per sec of integration, or better, is desirable, even a somewhat larger rms noise, $\sim 5 \div 10$ mK per sec of integration, is good enough to observe a significant number of sources.

b) **Atmospheric contamination**. The "stationary" atmospheric emission can be accurately modeled in data analysis by using the available atmospheric models and its effect can be significantly removed by taking advantage from the scan observation technique (see, e.g., Mandolesi et al. 1998b). The variability of the atmospheric contamination, the so-called atmospheric noise, is more crucial. Although the use of two frequency channels, one of them designed to monitor atmospheric contamination, helps in the subtraction of the atmospheric noise, it is crucial to test in site that the atmospheric noise is small enough to avoid a significant degradation of the sensitivity.

c) **A-priori pointing accuracy**. This seems to be not a particular critical point. Galactic HII regions are typically relatively extended (comparable with the beam FWHM), and a scan of 1–2 degrees is not dramatic. It could be also used as a resource in the observations of sky regions rich of Galactic HII regions.

d) **Accurate beam reconstruction and calibration**. Very bright and point-like sources can be used to accurately reconstruct the beam shape independently of the accurate knowledge of their fluxes; Jupiter is the most favourite candidate (see, e.g., Burigana et al. 2000b and references therein), since its relevant flux at millimeter wavelengths. Although the sensitivity considered here is relatively low, combining the data from many exposures can in principle allow to measure the beam shape up to response level low enough to permit also a good reconstruction of the beam solid angle. Jupiter, but also many other very bright sources in the sky, can be used to calibrate the data (see, e.g., Bersanelli et al. 1997 and references therein). The brightness temperature of planets is typically known with a relative accuracy of some %. Although not particularly high, this accuracy is good enough, compared with the S/N ratios the can be achieved for the majority of the Galactic HII regions (see, for example, Fig. 3), while it is of course one of the most important source of error for the brightest sources. The stability of the calibration during the many exposures of the observation night is also very crucial. In the case of significant calibration drifts, additional calibration exposures have to be included in the observation plan. This has to be tested in site in real conditions. In presence of $1/f$ noise like drifts due to possible gain fluctuations, destriping algorithms (see, e.g., Maino et al. 2002 and references therein) can in principle to be applied during the data analysis to subtract the drifts.

Once the above points are verified, it will be important to properly:

e) **Plan the observation campaign**. It is necessary to identify the most favorable regions of the sky, with attention to: the apparent position of the sources at the date of observation, the richness of the region to be observed, the estimated brightness and diameter of the sources.

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Figure 1: Distribution function and cumulative distribution function of the S/N ratios for an instrument sensitivity of 30 mK per second of integration. The dotted lines refer to the case of a *single exposure* while the dashed lines refer to the case of a *one night* observation; for the both cases, the lower (thin) lines refer to the distribution functions and the upper (thick) lines to the cumulative distribution functions. See also the text.

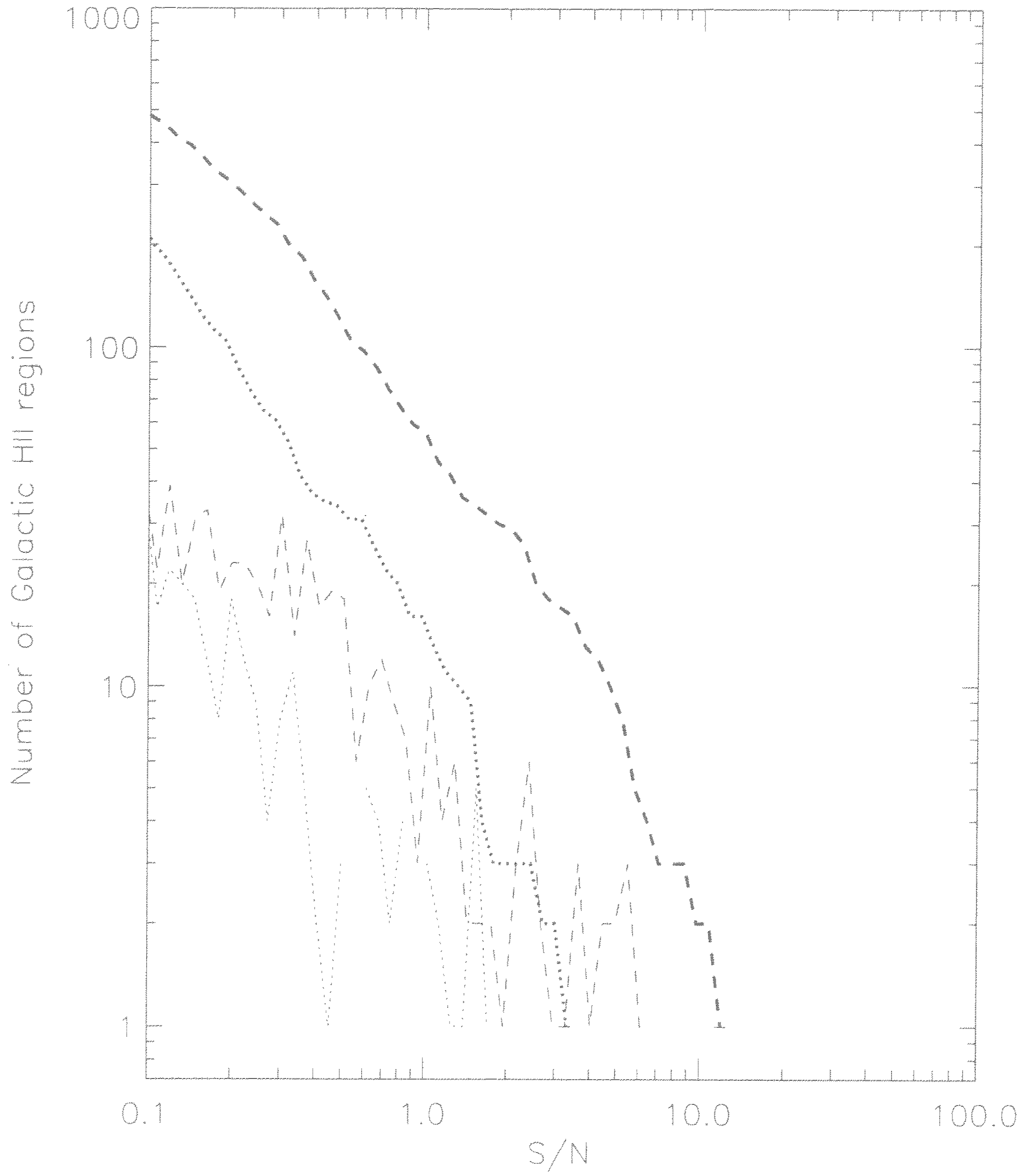


Figure 2: The same as in the previous figure but for an instrument sensitivity of 10 mK per second of integration.

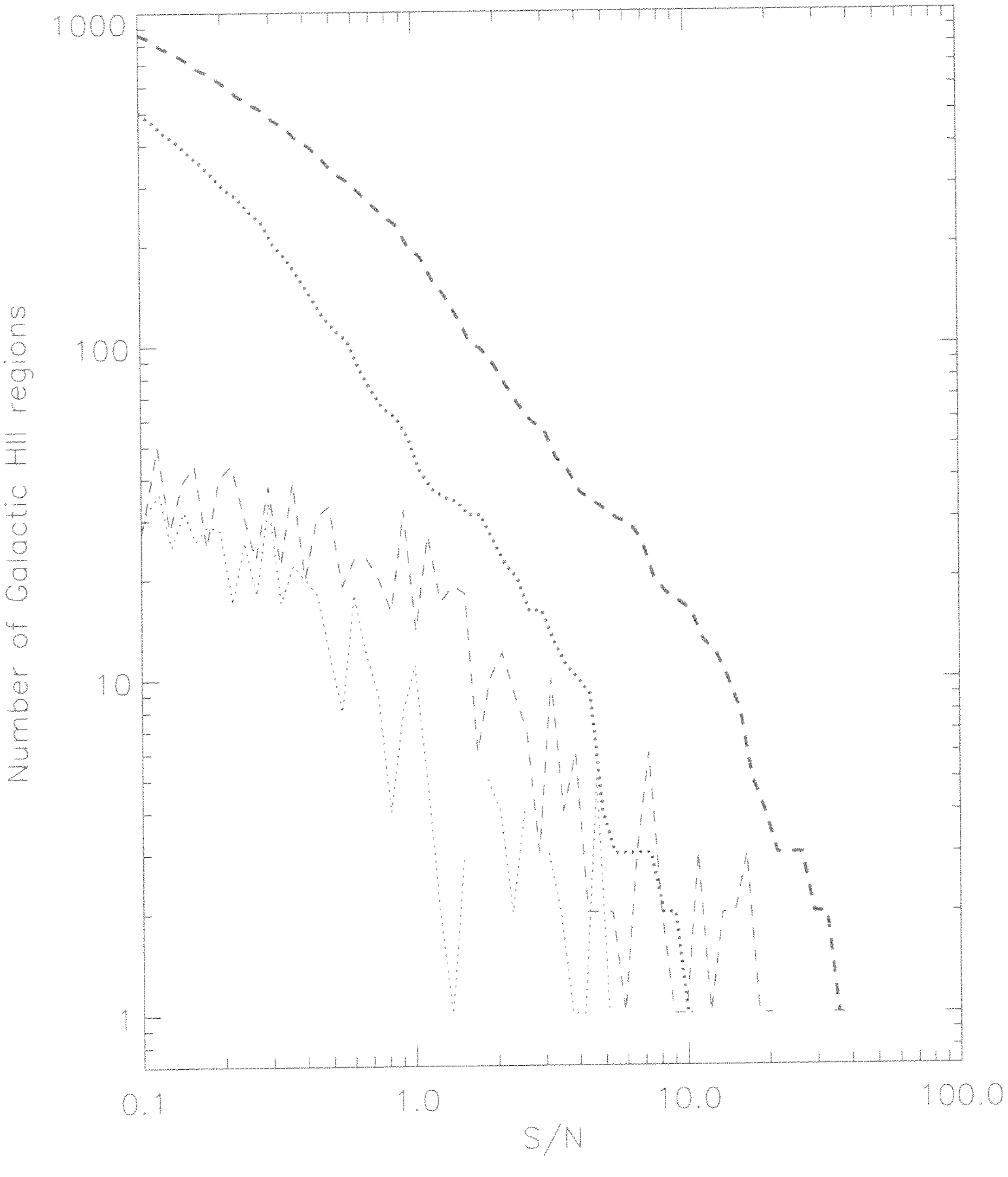
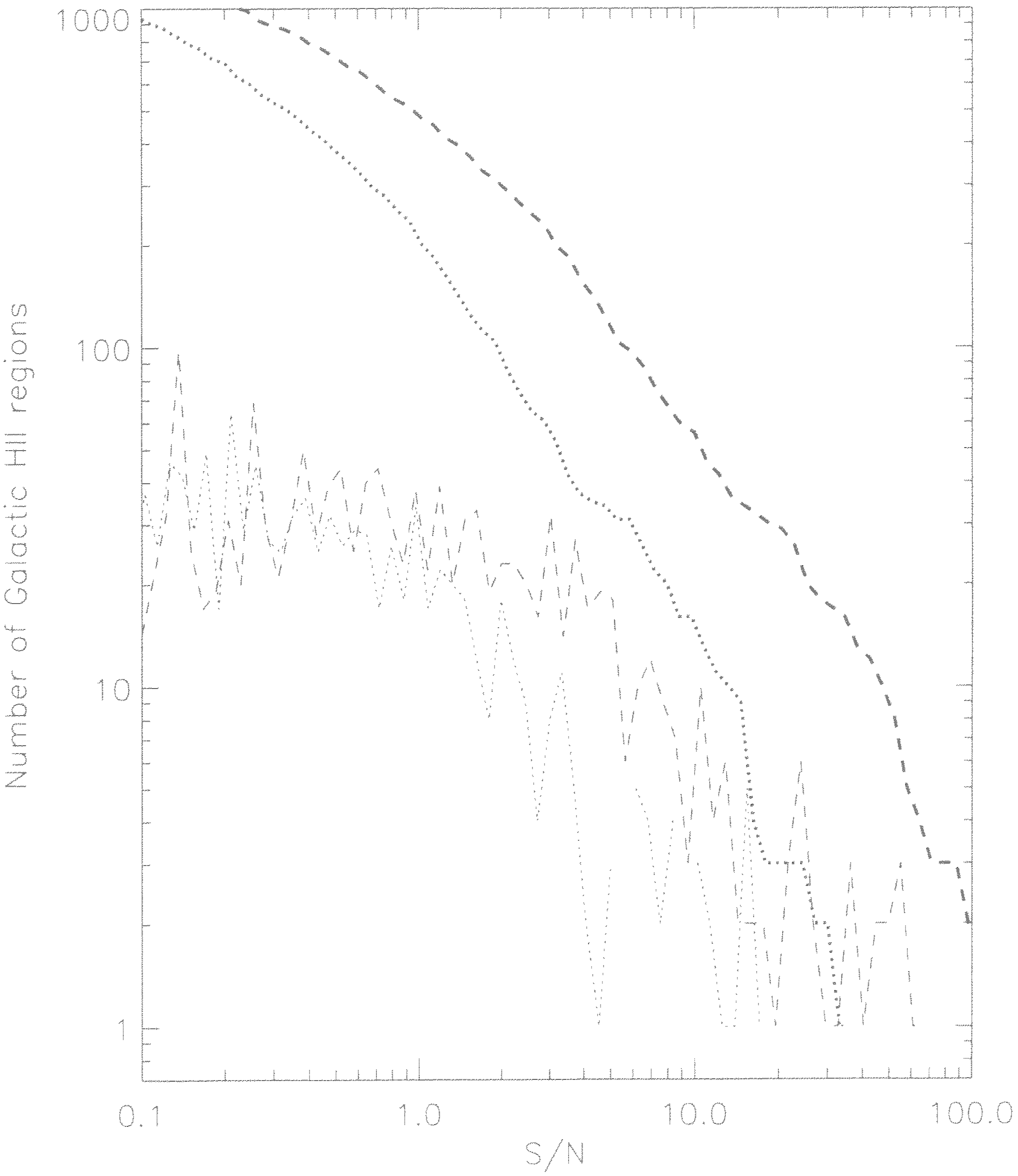


Figure 3: The same as in the previous figure but for an instrument sensitivity of 3 mK per second of integration.



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