Astronomy & Astrophysics manuscript no. 3933 December 11, 2007
(DOI: will be inserted by hand later)

AGB stars in the Magellanic Clouds. II. The rate of star formation across the LMC.

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Received 27 Jyly 2005/ Accepted ...

Abstract. This article compares the distribution of K_s magnitudes of Large Magellanic Cloud (LMC) asymptotic giant branch (AGB) stars obtained from the DENIS and 2MASS data with theoretical distributions. These have been constructed using up-to-date stellar evolution calculations for low and intermediate-mass stars, and in particular for thermally pulsing AGB stars. A fit of the magnitude distribution of both carbon- and oxygen-rich AGB stars allowed us to constrain the metallicity distribution across the LMC and its star formation rate (SFR). The LMC stellar population is found to be on average $5-6$ Gyr old and is consistent with a mean metallicity corresponding to $Z=0.006$. These values may however be affected by systematic errors in the underlying stellar models, and by the limited exploration of the possible SFR histories. Instead our method should be particularly useful for detecting variations in the mean metallicity and SFR across the LMC disk. There are well defined regions where both the metallicity and the mean-age of the underlying stellar population span the whole range of grid parameters. The C/M ratio discussed in paper I is a tracer of the metallicity distribution if the underlying stellar population is older than about a few Gyr. A similar study across the Small Magellanic Cloud is given in paper III of this series.

1. Introduction

Asymptotic Giant Branch (AGB) stars are among the brightest infrared members of a galaxy. They are useful indicators of galactic structure because they are widely distributed and easily noticed, and the ratio between carbon-rich (C-rich or C-type) and oxygen-rich (O-rich or M-type) AGB stars is an indicator of metallicity. Cioni & Habing (?) – Paper I – showed that this ratio varies over the face of the Large Magellanic Cloud (LMC) and concluded that a metallicity gradient is present in this galaxy; within the Small Magellanic Cloud (SMC) there are variations in this ratio but there is no clear pattern. Because AGB stars trace the stellar populations from ~ 0.1 to several Gyr, we want to constrain the global star formation rate (SFR) of the Magellanic Clouds, interpreting the large-scale magnitude distribution of AGB stars in the K_s band with the help of up-to-date stellar models. This work focuses on the stellar population in the field; we do not discuss clusters and associations. Although almost all previous work, a summary of which is given below, has been based on information from small regions within each galaxy, they more or less agree on the time-scale of major star formation events but it is not yet clear what these events were and what caused them.

Section **??** describes our selection of the sample of AGB stars from the DENIS catalogue towards the Magellanic Clouds (DCMC) and from the 2MASS catalogue. Section **??** describes the theoretical models used to construct a magnitude distribution while Sect. **??** compares the observed and theoretical distributions. Section **??** contains a comparison of our results with the information known from the literature while section **??** concludes this paper. A similar study of the star formation rate in the SMC is presented in paper III of the series.

1.1. SFR in the LMC - Review

The LMC is a disk galaxy within which a bar is embedded. The disk, elongated toward the Galactic center, perhaps because of the tidal force induced by the Milky Way, is elliptical with ellipticity $\epsilon = 0.199 \pm 0.008$; it is viewed at an inclination angle $i = 34^\circ.7 \pm 6^\circ.2$ and a position angle of the major axis $\mathrm{PA_{maj}} = 189^\circ.3 \pm 1^\circ.4$ (van der Marel ?, van der Marel & Cioni ?). The off-center bar is about 3° long, it is inclined at $15^\circ.1 \pm 2^\circ.7$ such that the eastern side is closer to us than the western side (Subramaniam

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?). The LMC thickness (about 2.4 kpc, Lah et al. ?) is almost negligible compared to its distance.

The majority of the LMC globular cluster population is about $3-4$ Gyr old and perhaps results from a tidal interaction with the SMC (van den Bergh ?, Bekki et al. ?). A few globular clusters formed before 11.5 Gyr ago and during recent distinct episodes of cluster formation (Hodge ?, Subramaniam ?, and references therein). Most star clusters dissolve in the LMC after about 1 Gyr (Hodge ?) and then contribute to a stellar population in the field that is of varying age and metallicity. A decoupling between the rate of cluster formation and the SFR suggests that clusters may not be good tracers of the star formation in general (van den Bergh ?).

Pioneering studies of different types of stars (Tifft & Snell ?) and of their distribution as a function of age (Isserstedt ?) lead us to discover that the bulk of the LMC disk stellar population formed $3-5$ Gyr ago (Butcher ?). Some M giants (mostly AGB stars) as well C-rich AGB stars in the centre of the bar formed during this burst and others during another episode about 0.1 Gyr ago (Frogel & Blanco ?, Wood et al. ? – Fig. ??). This latter episode, possibly associated with a close encounter with the SMC, has produced a burst of star formation in both galaxies. It is supported by the distribution of early-type stars (Kontizas et al. ?) and has been confirmed by the MACHO project comparing stellar evolution and pulsation models of Cepheids with their observed period-frequency distribution (Alcock et al. ?). The same study also suggests that during the last 0.1 Gyr star formation has been propagating from the South-East (SE) to the North-West (NW) along the bar where it is still ongoing (Hardy et al. ?, Fig. ??). The formation of supergiant (massive) stars occured more recently, about 7.5 Myr ago (Ardeberg ?, Feitzinger et al. ?).

Olson & Pefia (?) postulated a constant birthrate interrupted by periods of higher than average star formation. However, Rocca-Volmerange et al. (?), by comparing integrated colours of the Magellanic Clouds with an evolutionary model, concluded that the evolution has been smooth, with a steady or slightly decreasing SFR in the past. Significant variations in the bolometric luminosity of AGB stars point to differences in the star formation history across the field (Reid & Mould ?, Fig. ??). In particular carbon stars at the periphery might be younger (Costa & Frogel ?, Fig. ??).

Deep B and V band observations were compared by Bertelli et al. (?, Fig. ??) and by Vallenari et al. (?, ?, Fig. ??) with synthetic colour-magnitude-diagrams and luminosity functions (LFs). The authors concluded that from region to region star formation took place at different epochs. In particular, the SFR in some fields was low until 4 ± 0.5 Gyr ago, but this burst would occur about 2 Gyr later if the models include overshooting; the SFR was enhanced $6-8$ Gyr ago in the region East (E) of the bar while in the region West (W) of the center there was star formation $2-3$ Gyr ago. About 8° from the LMC center Gallart et al. (?, Fig. ??) using high quality V and I photometry derived an intermediate age (> 2.5 Gyr old) stellar population as well as a younger (≈ 1.5 Gyr old) component which is perhaps the result of an LMC-SMC encounter or from a merger of the LMC with a smaller galaxy. Although there is an indication of an age gradient, in the sense: "older stars towards the periphery" (> 8 Gyr old), there is only a small population as old and metal poor as that of the Milky Way halo globular clusters and dwarf spheroidal galaxies (see also Stryker ?).

Observations with the Hubble Space Telescope (HST) in the LMC outer disk revealed for the first time the oldest main-sequence turnoff point (Gallagher et al. ?, Fig. ??). A best fit model of the main-sequence suggests a roughly constant SFR over 10 Gyr with an increase around 2 Gyr (Holtzman et al. ?, Geha et al. ? – Fig. ??) although in the vicinity of the globular cluster NGC 1866 an increase in the star formation rate probably occurred a Gyr earlier (Stappers et al. ?, Fig. ??). A relatively larger component of older stars around globular clusters was also found by Olsen (?, Fig. ??). In the inner disk a burst at about 1 Gyr may correspond to the formation of the bar (Elson et al. ?, Fig. ??) but an older bar ($4-6$ Gyr) was claimed by Smecker-Hane et al. (?, Fig. ??). Differences in either age or metallicity were detected between this inner disk field and the outer disk field studied by Gallagher et al. (?). Near the bar Javiel et al. (?, Fig. ??) confirm a stars forming event at 1 Gyr and one before 10 Gyr (see also Holtzman et al. ?, Fig. ??) with a clear gap from $3-6$ Gyr. In the centre of the bar Ardeberg et al. (?, Fig. ??) identify two strong populations: a young component that originated about 0.5 Gyr ago and an older component that originated between 2 and 9 Gyr ago.

Thus, information about the star formation history of the LMC has been obtained from the study of many relatively small regions located in the outer and inner disk as well as along the bar. There are regions of the galaxy that can be described by a relatively uniform SFR across several Gyr. The dominant stellar population is of intermediate-age (> 2.5 Gyr) and extends to the remote periphery. A burst of star formation has occurred between 1 and 3 Gyr; although some authors attribute to this event the formation of the bar, there is evidence that stars as old as $4-8$ Gyr exist in the bar as well as in the disk. Only a detailed kinematic study of the stellar population will reveal its distinct components. This as well as more recent bursts of star formation are probably due to a close passage with the Mikly Way and the SMC. In the outer disk, searches for stars similar to those in the halo of the Milky Way have shown that metal poor old giants are lacking. AGB stars formed essentially during two major epochs: around 10^8 yr ago for the most massive and a few Gyr ago for lower masses. Globular clusters are older than about 11 Gyr or younger than about 4 Gyr.

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Erratum
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A&A 448, 77-91 (2006), DOI: 10.1051/0004-6361:20053933

Abstract. An abstract should be given

Figure 1 shows the distribution of mean-age and metallicity across the LMC accounting correctly for the orientation of the galaxy in the sky by applying different magnitude shifts to stars in different locations. This figure substitutes Fig. 14 in the published version of the paper which was obtained after applying a systematic shift of −0.12 mag to each star in each region.

In the new figure the most striking feature is an approximately smooth ring-like distribution of higher metallicity compared to the inner region of the galaxy containing the bar. This ring-like structure is obtained from both C- and O-rich AGB stars. The

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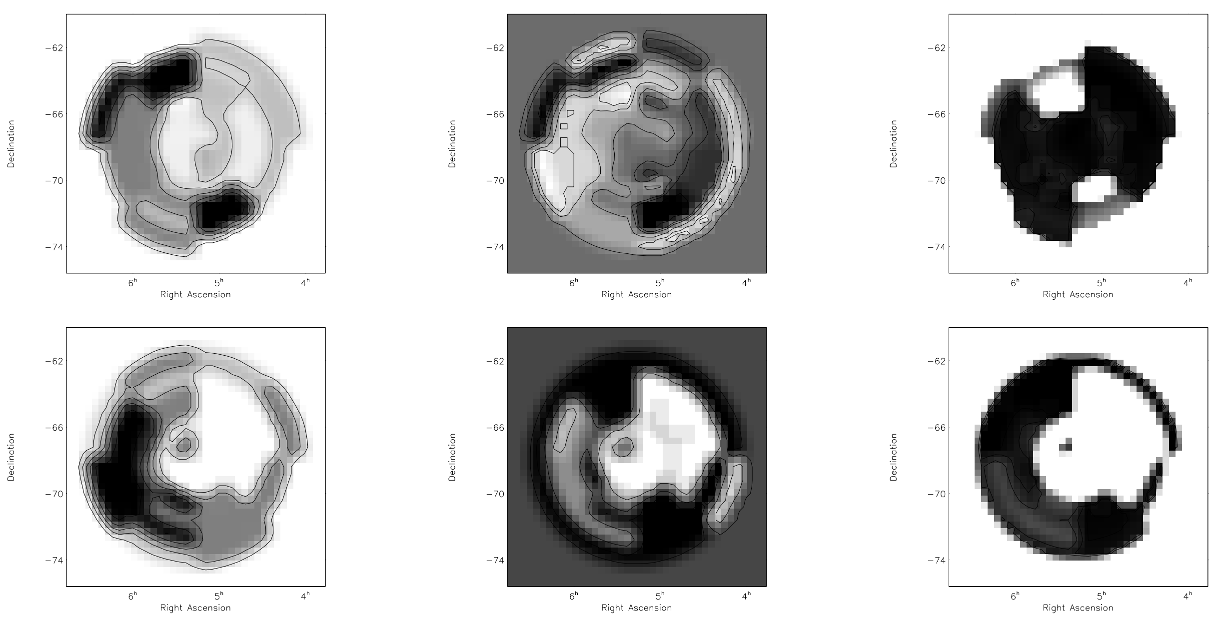
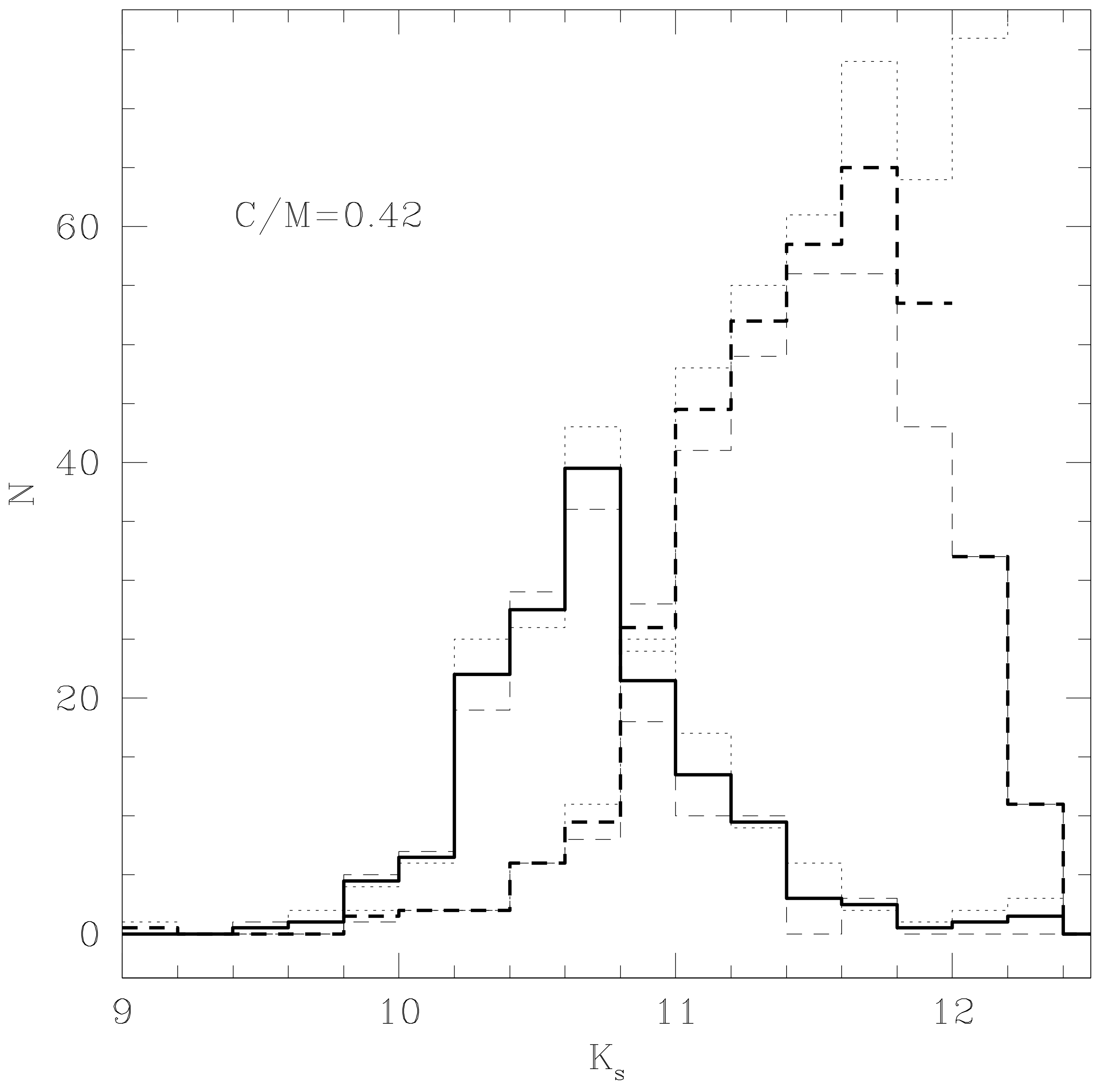


Fig. 1. The same as Fig. 11 but after correcting each sector in rings number 2 − 5 for the LMC orientation as in Table 2. Contour values are at: Z = 0.003 − 0.015 with a step of 0.003 for the distribution of metallicity obtained from both C-rich and O-rich AGB stars (*left*); 2, 3, 5, 7, 8, 10 Gyr and 3, 6, 8 Gyr for the distribution of mean-age obtained from C-rich (*middle-up*) and O-rich AGB stars (*middle-down*) respectively; 0.93, 0.96, 0.99 and 0.97, 0.98, 0.99 for the corresponding probability for which the grey scale shows only values above 0.6 and 0.8 for C-rich and O-rich AGB stars, respectively. Darker regions correspond to higher numbers.

average metallicity in the ring corresponds to $Z = 0.006$ while in the centre $Z < 0.003$. The distribution of mean-age across the galaxy points to a young stellar population in the E-SE compared to an older population in the W-SW. However, the distribution is rather patchy especially in regions poorly constrained (NE and SW). The bar of the galaxy does not appear as a clear feature but it corresponds to a population which is on average 5 Gyr old.

Note also that the isochrones used in this paper are now available at http://pleiadi.oapd.inaf.it .


C/M=0.42
N
Ks
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9
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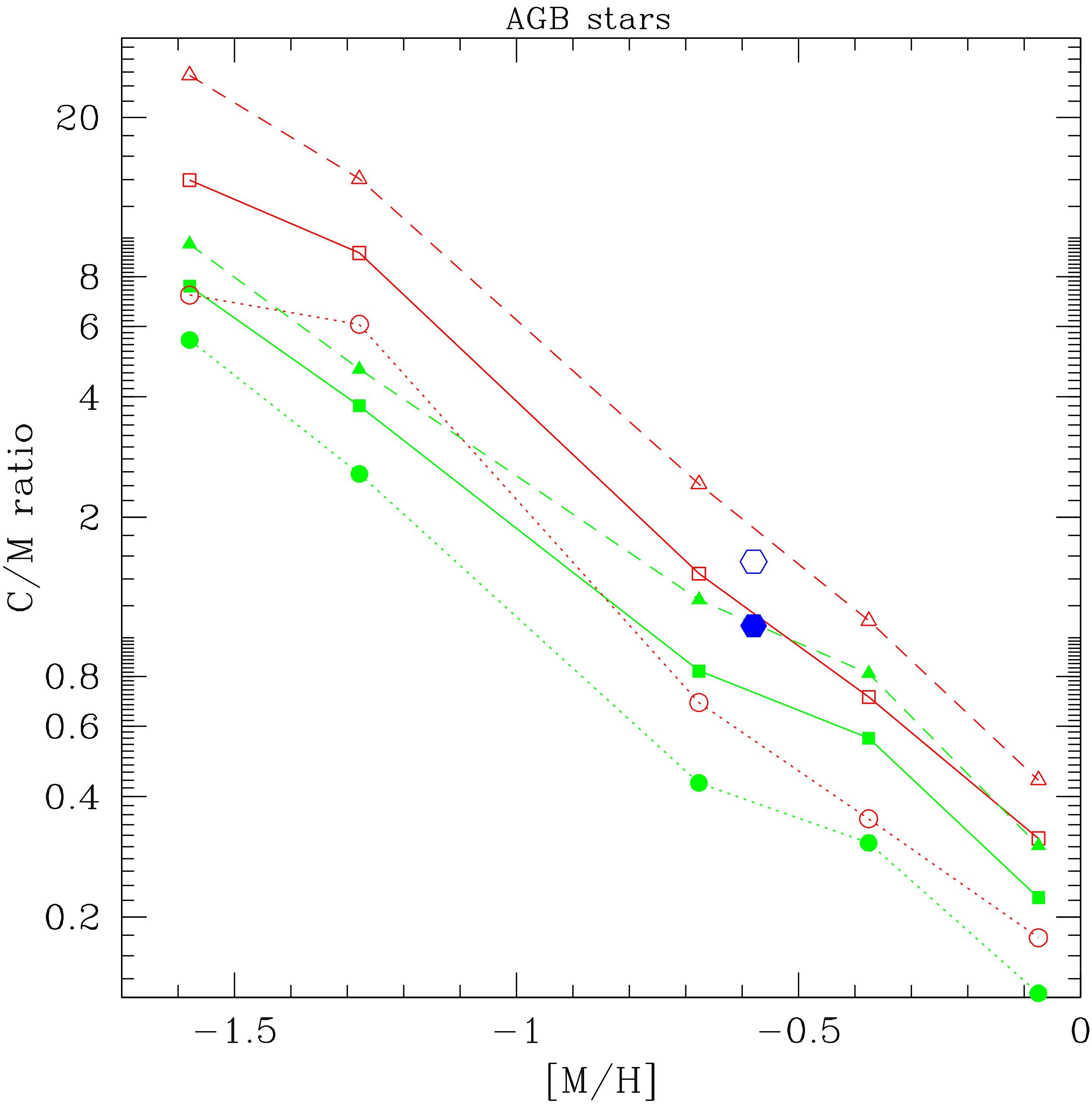
11
12


AGB stars
C/M ratio
[M/H]
20
8
6
4
2
0.8
0.6
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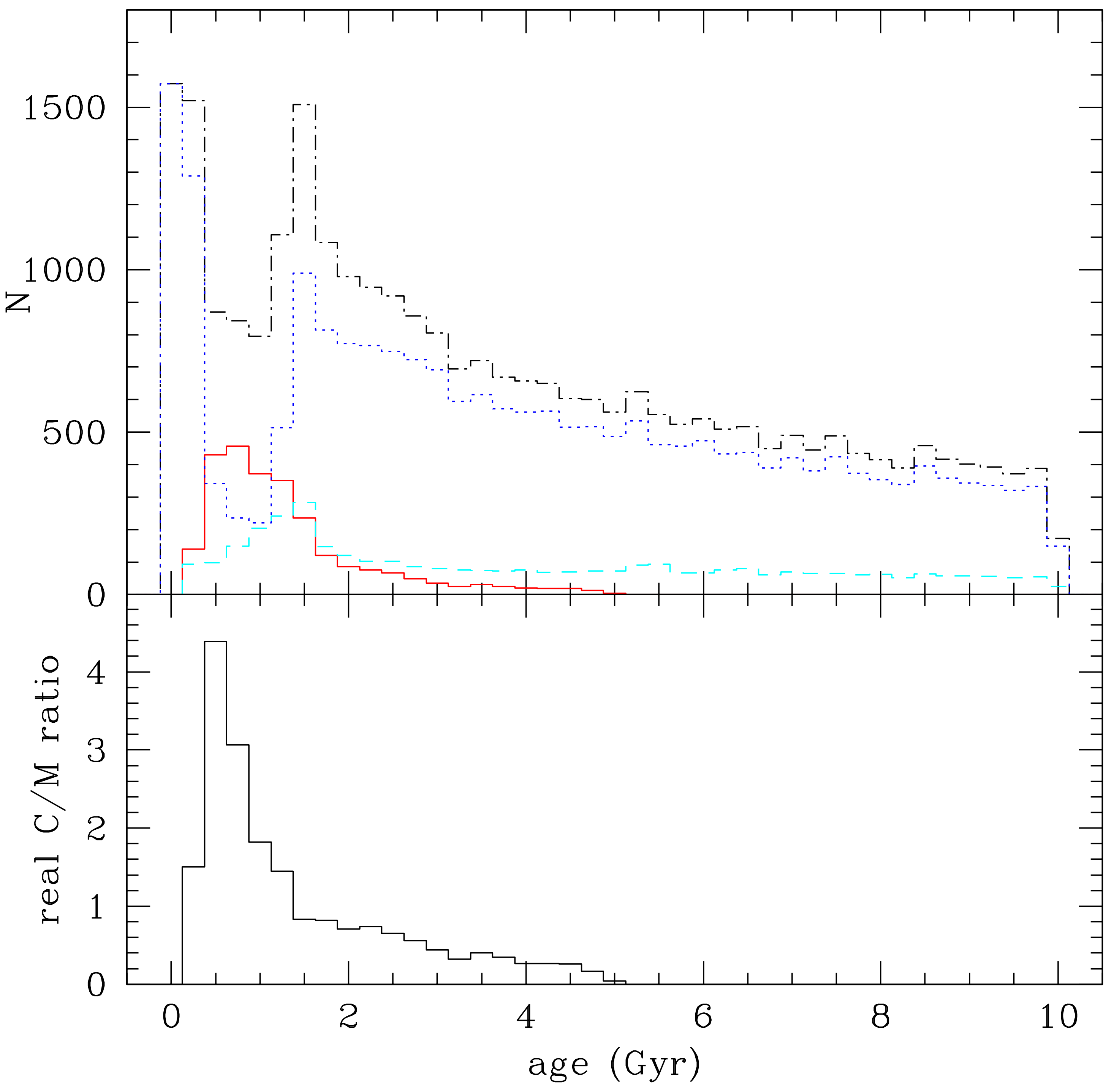

N
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real C/M ratio
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2
1
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0
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8
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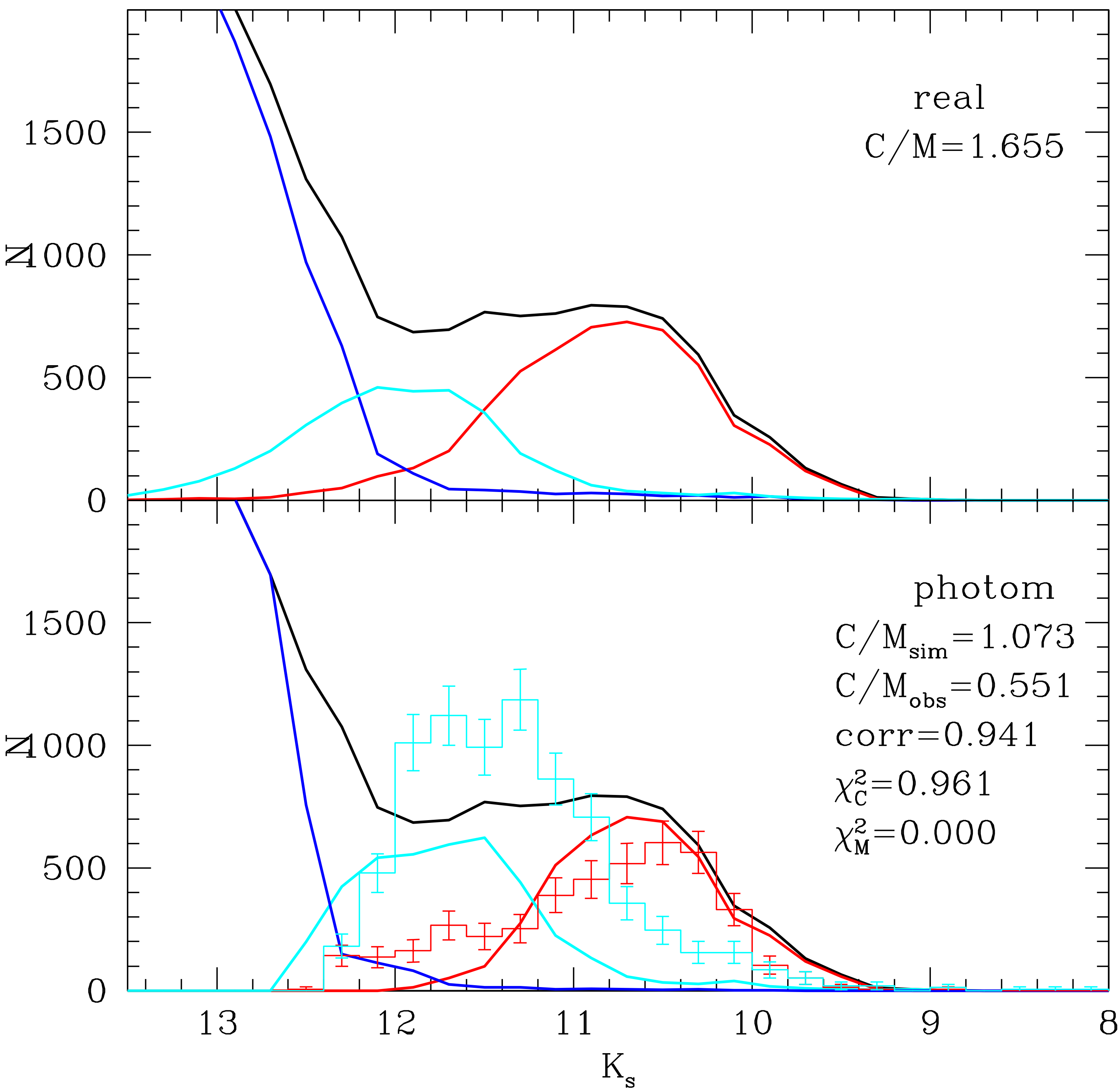
age (Gyr)


real
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photom
C/M$_{sim}$=1.073
C/M$_{obs}$=0.551
corr=0.941
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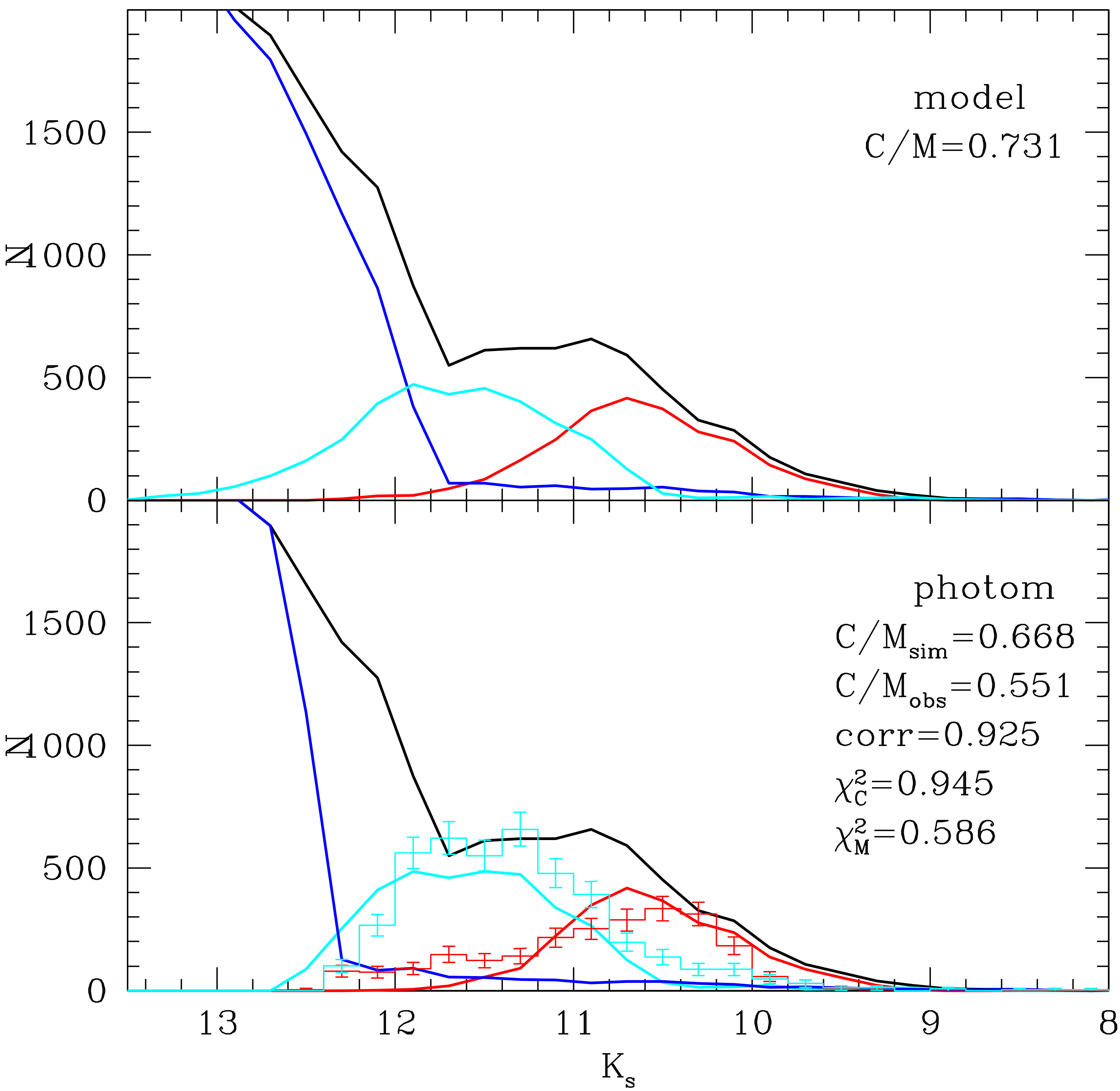

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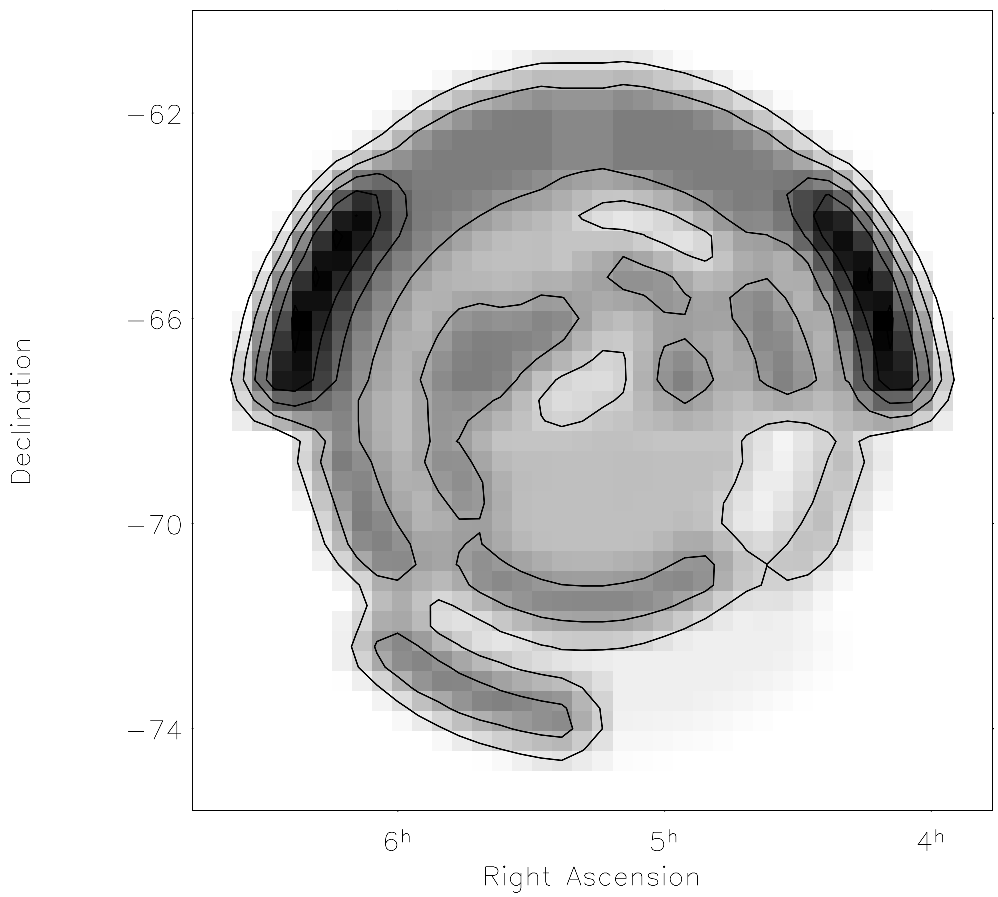
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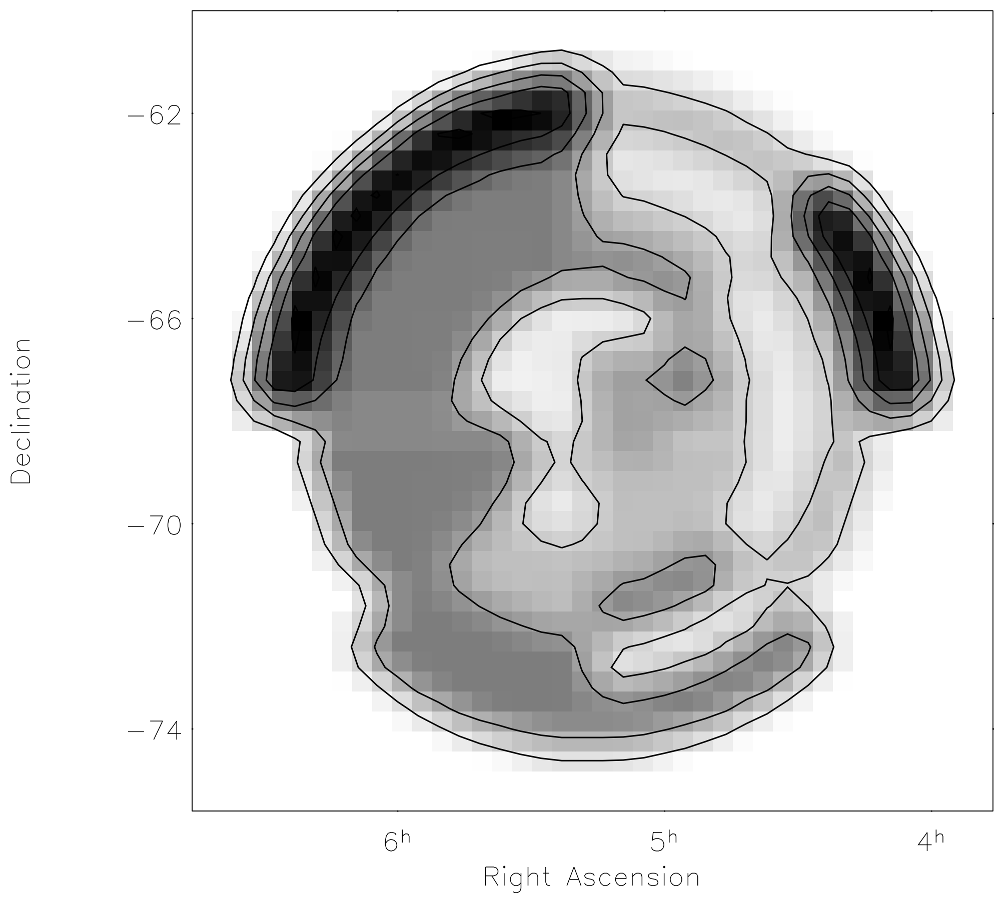

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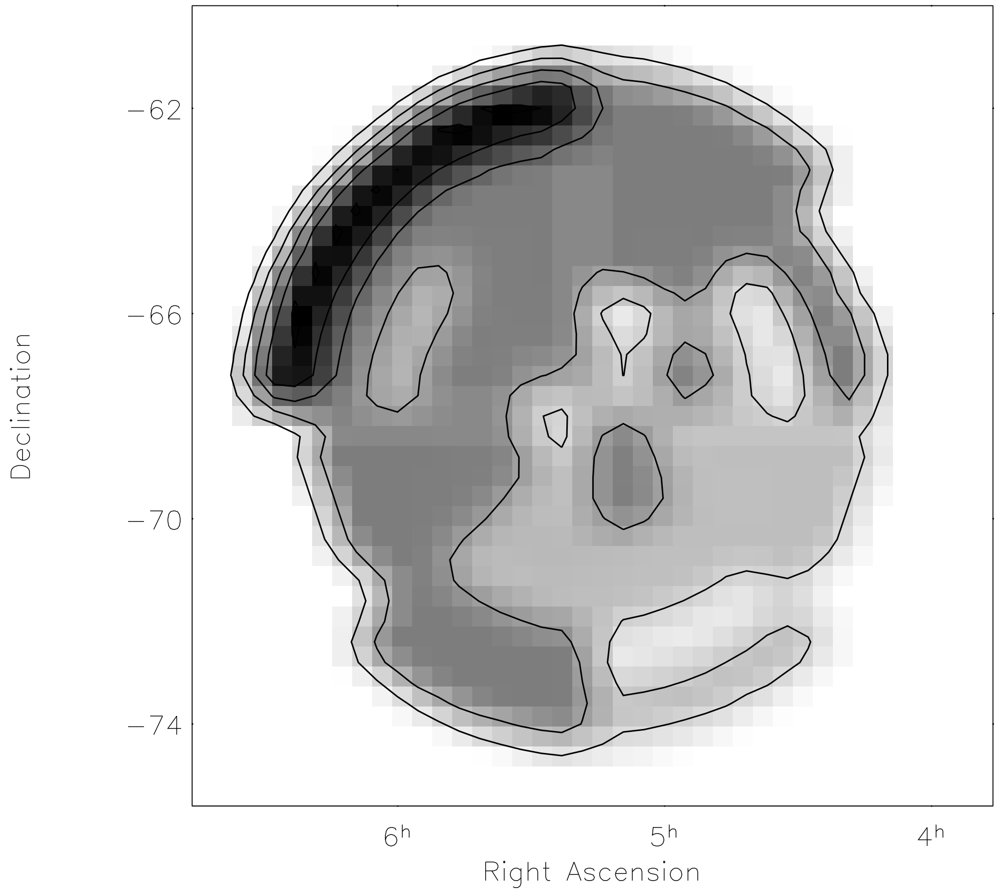

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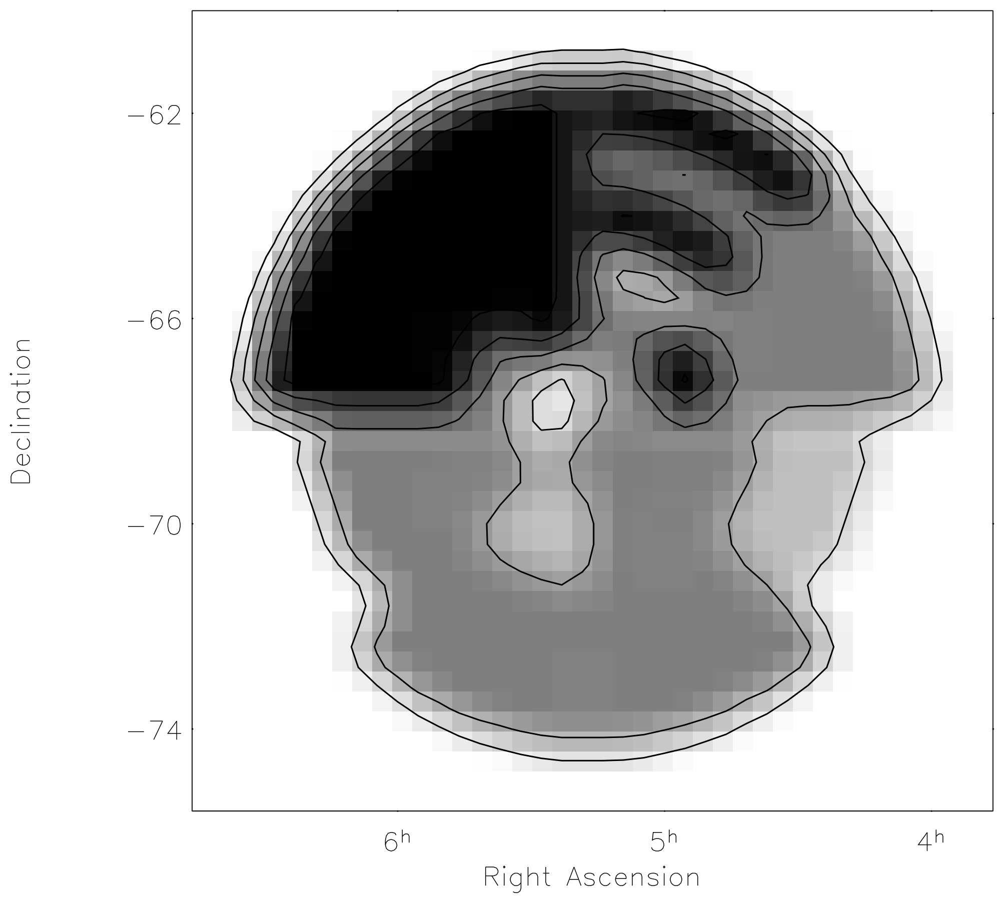

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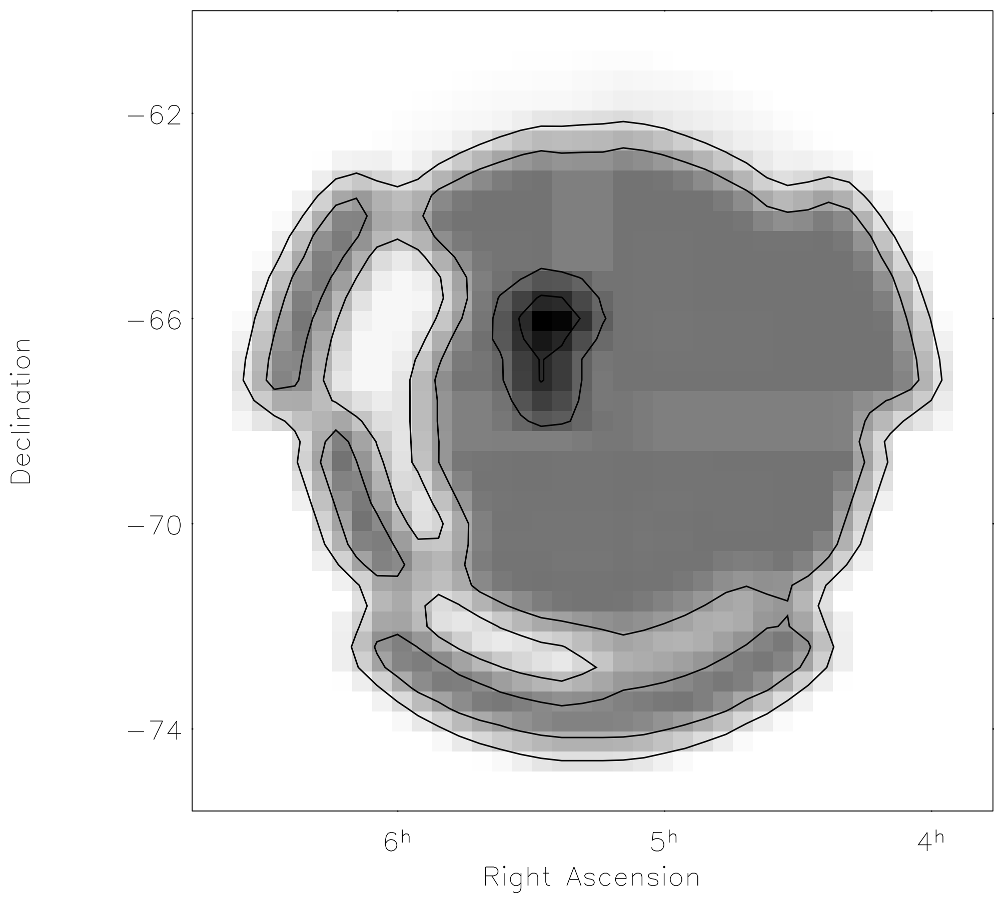

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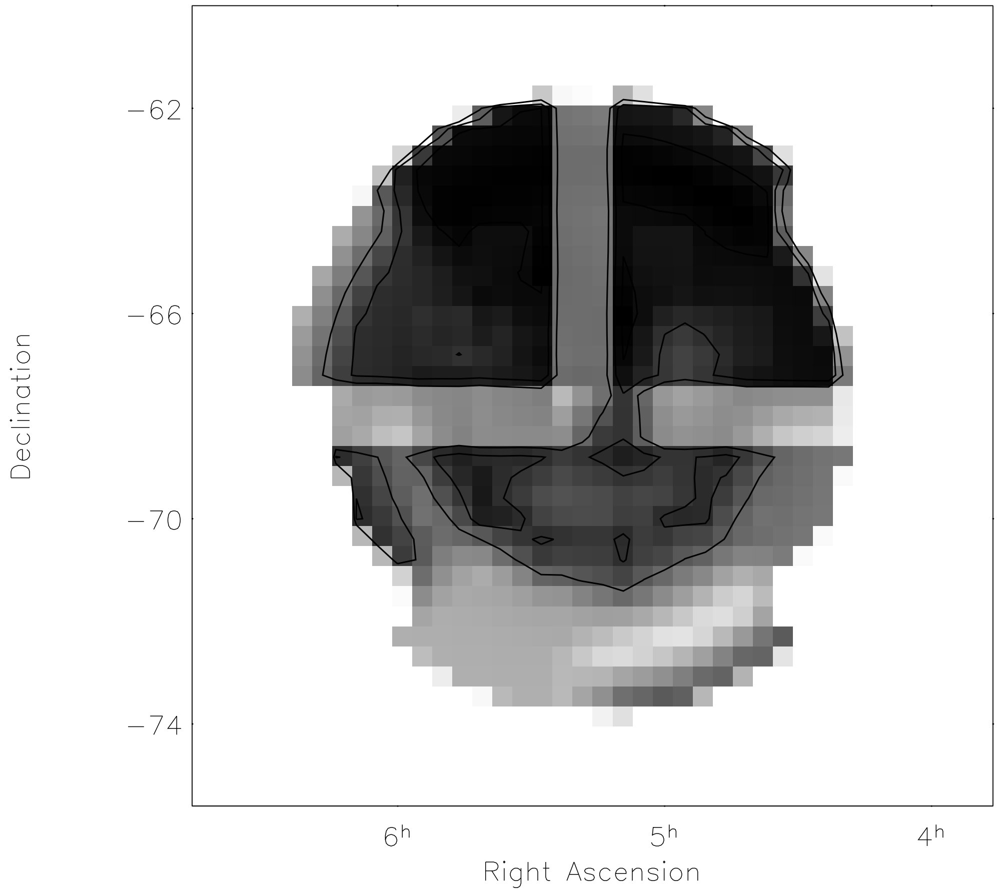

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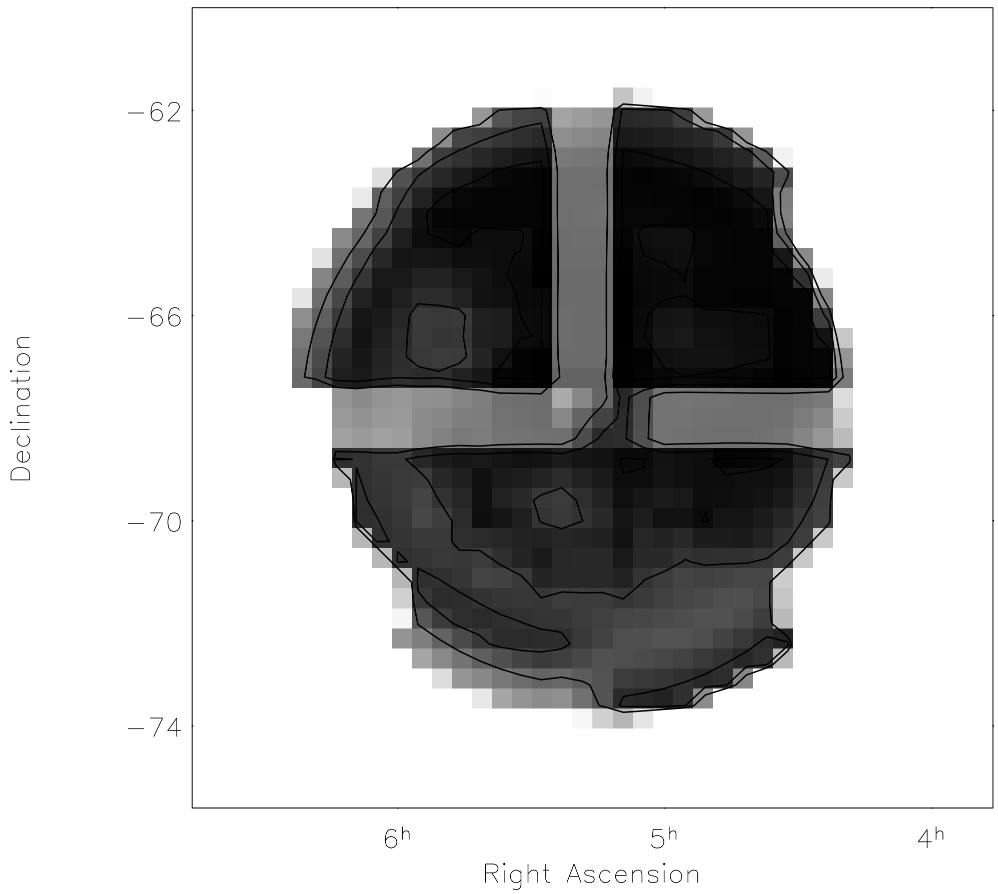

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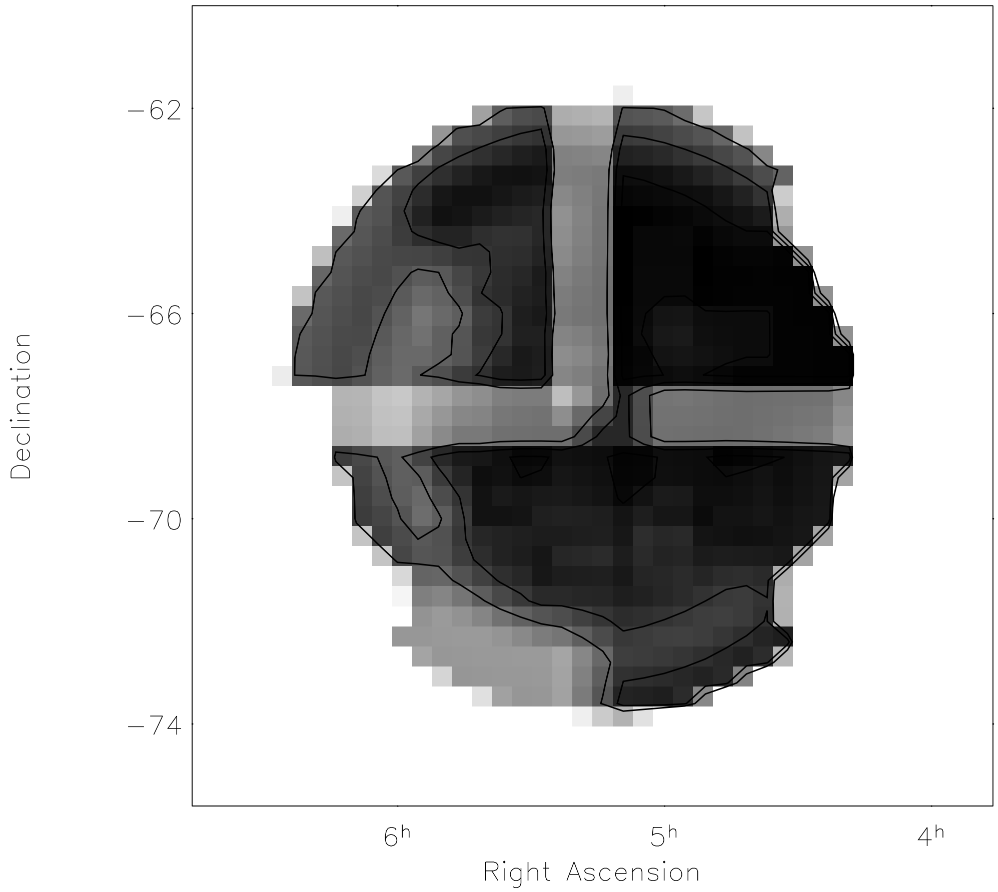

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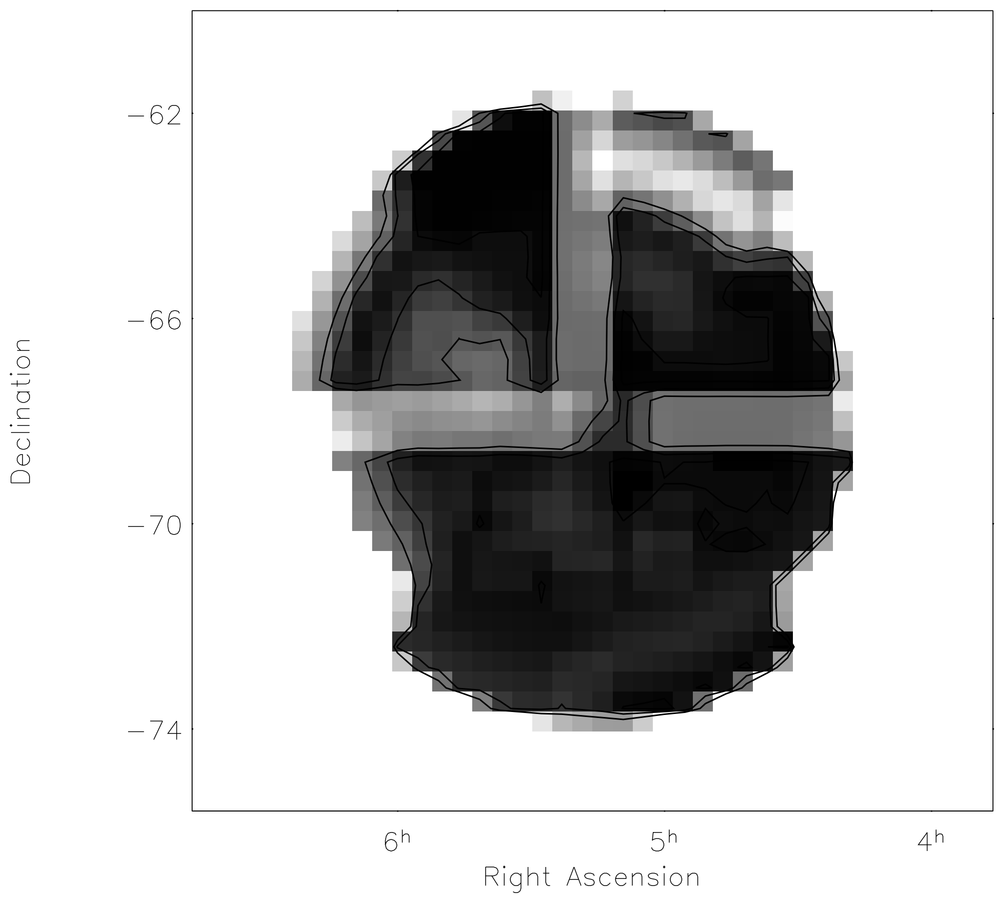

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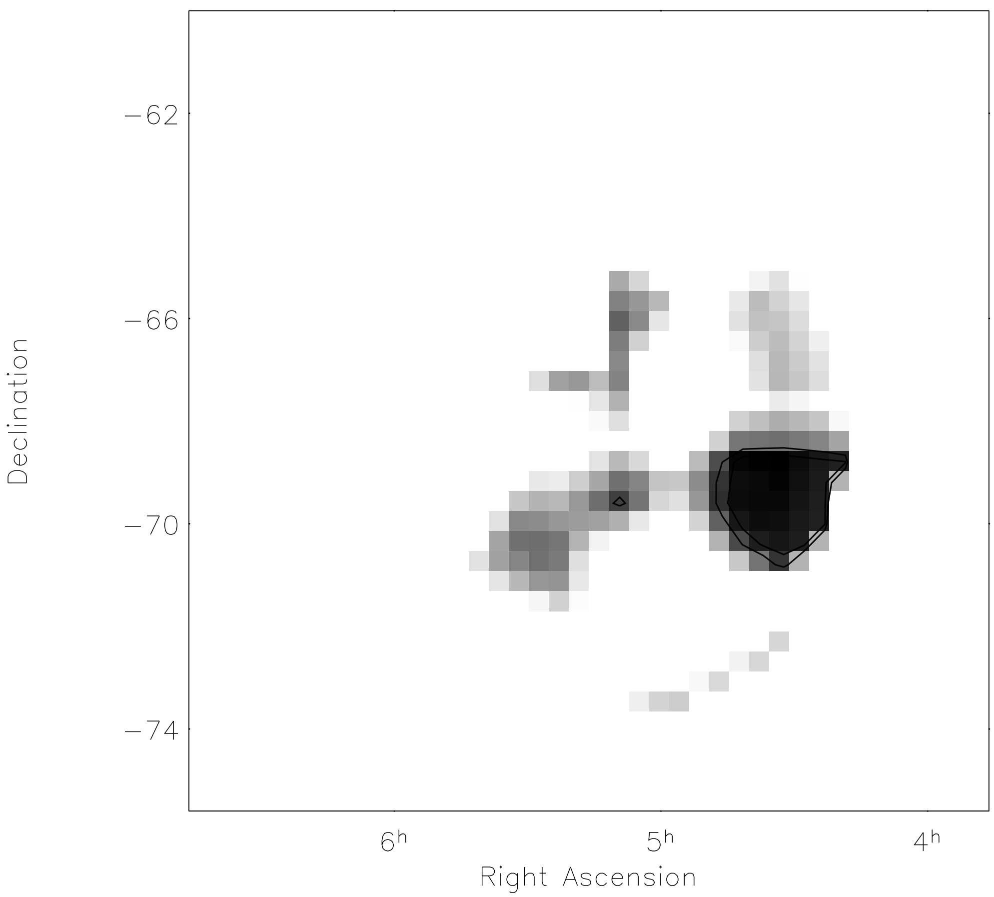
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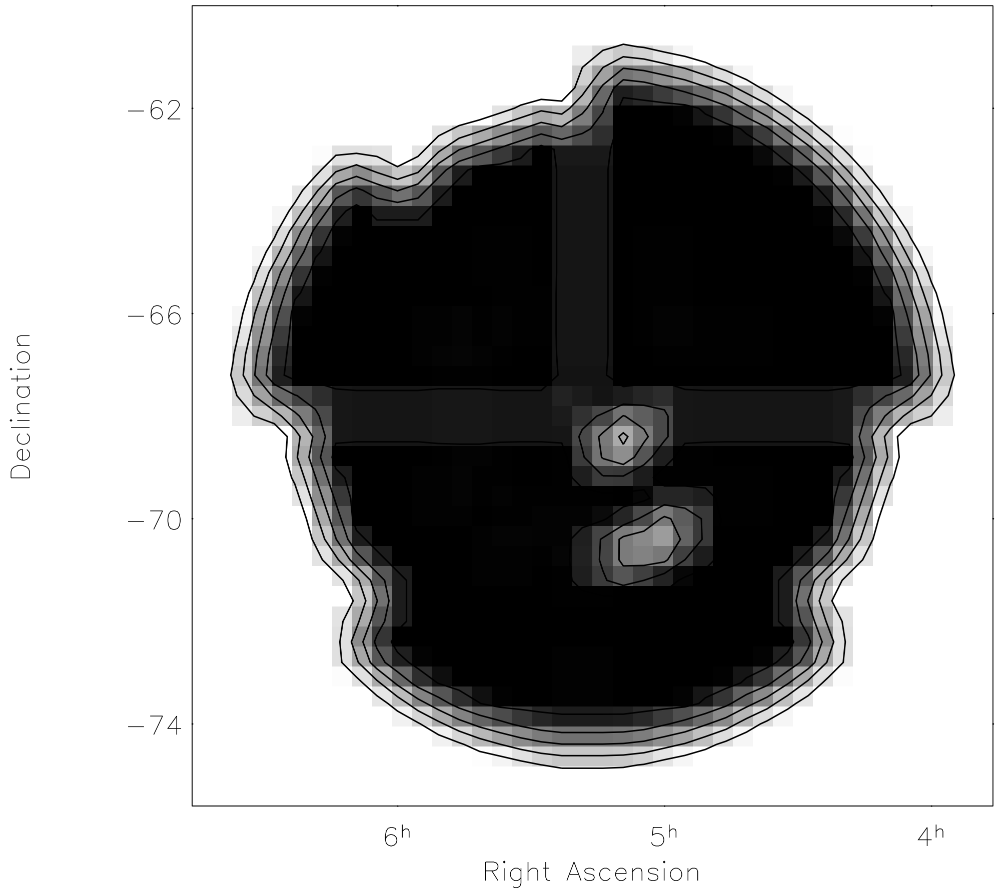
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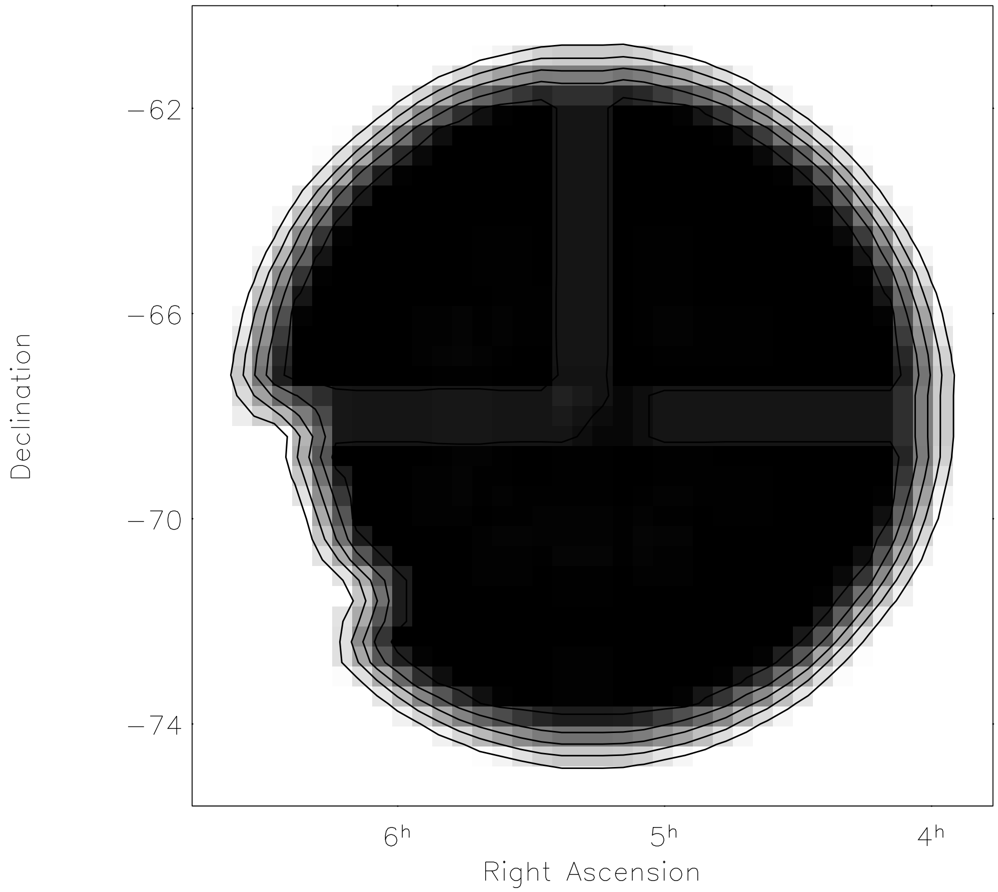

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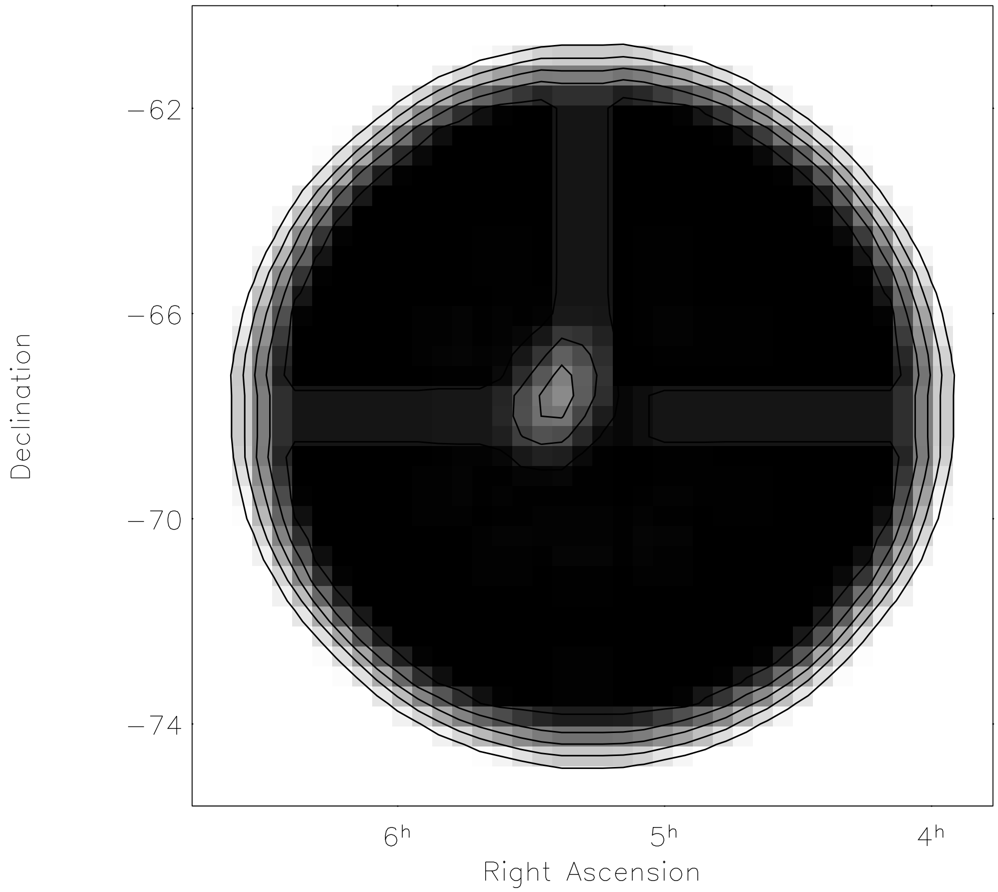

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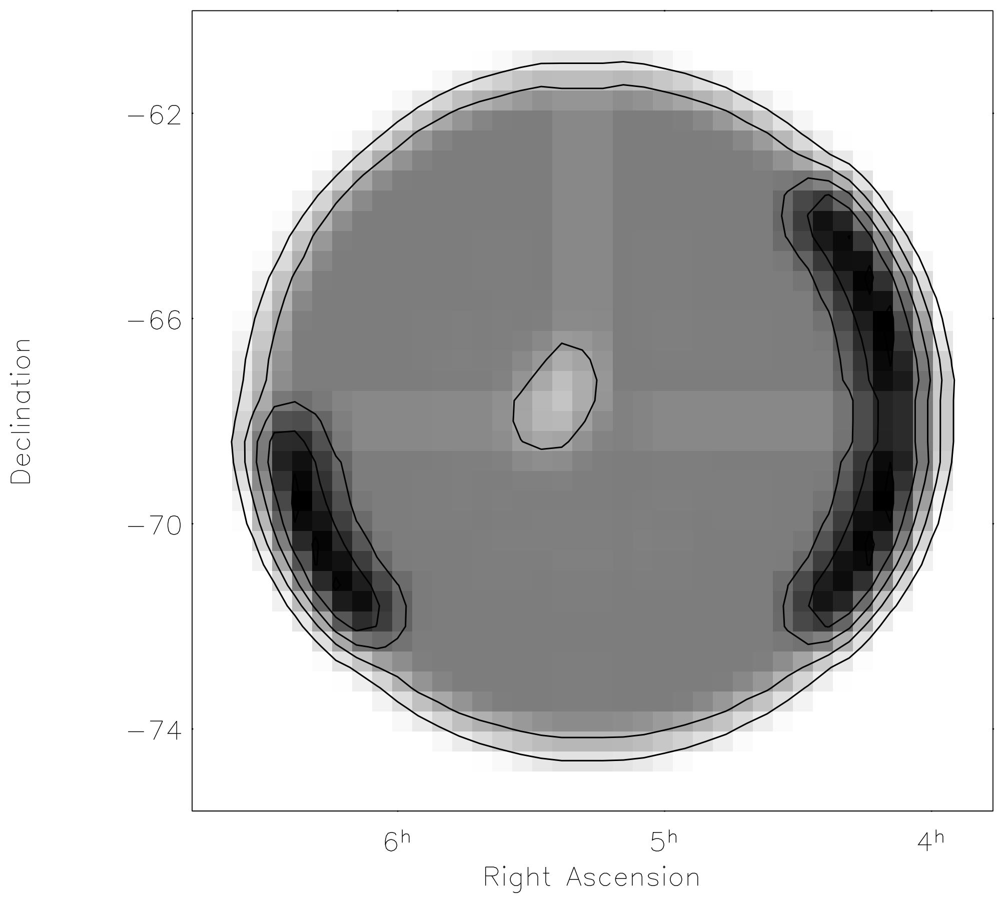
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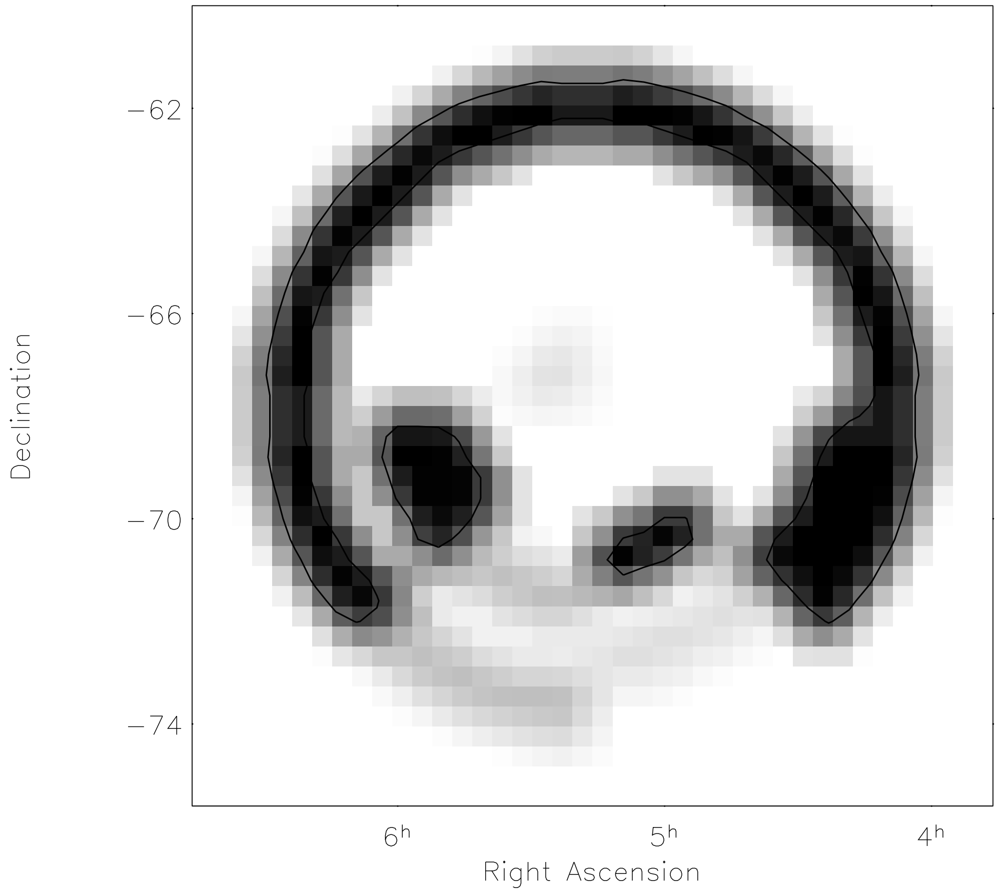

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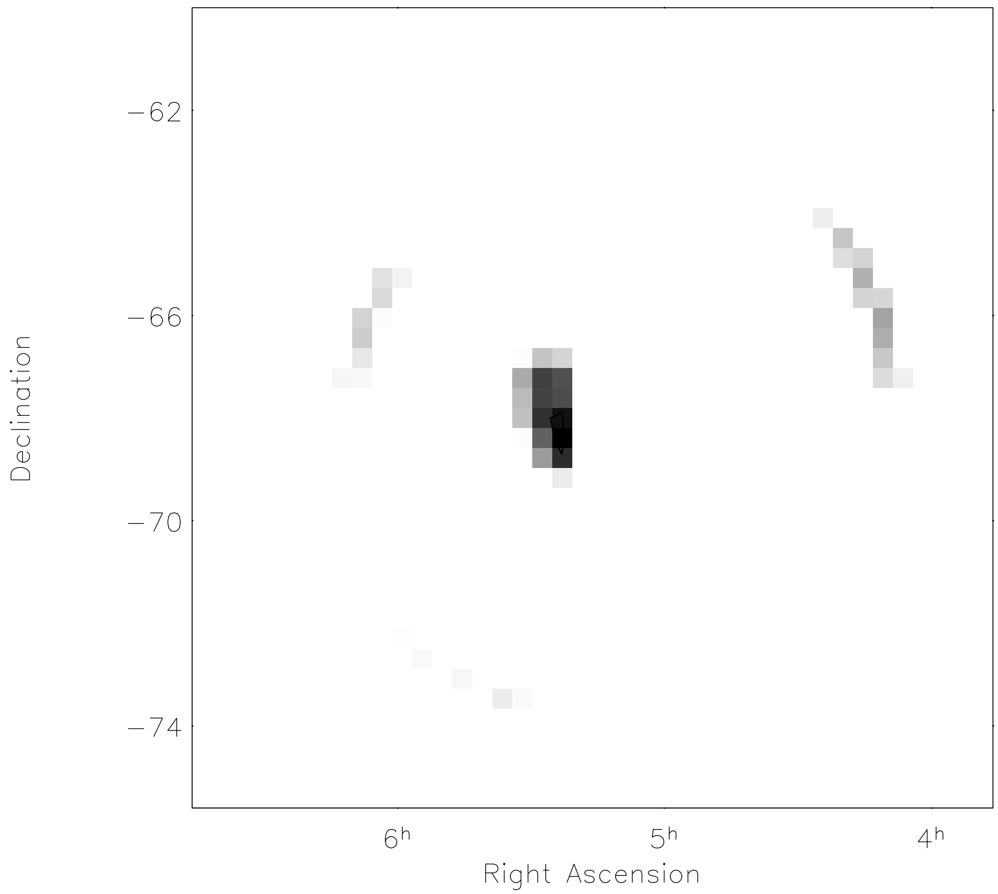

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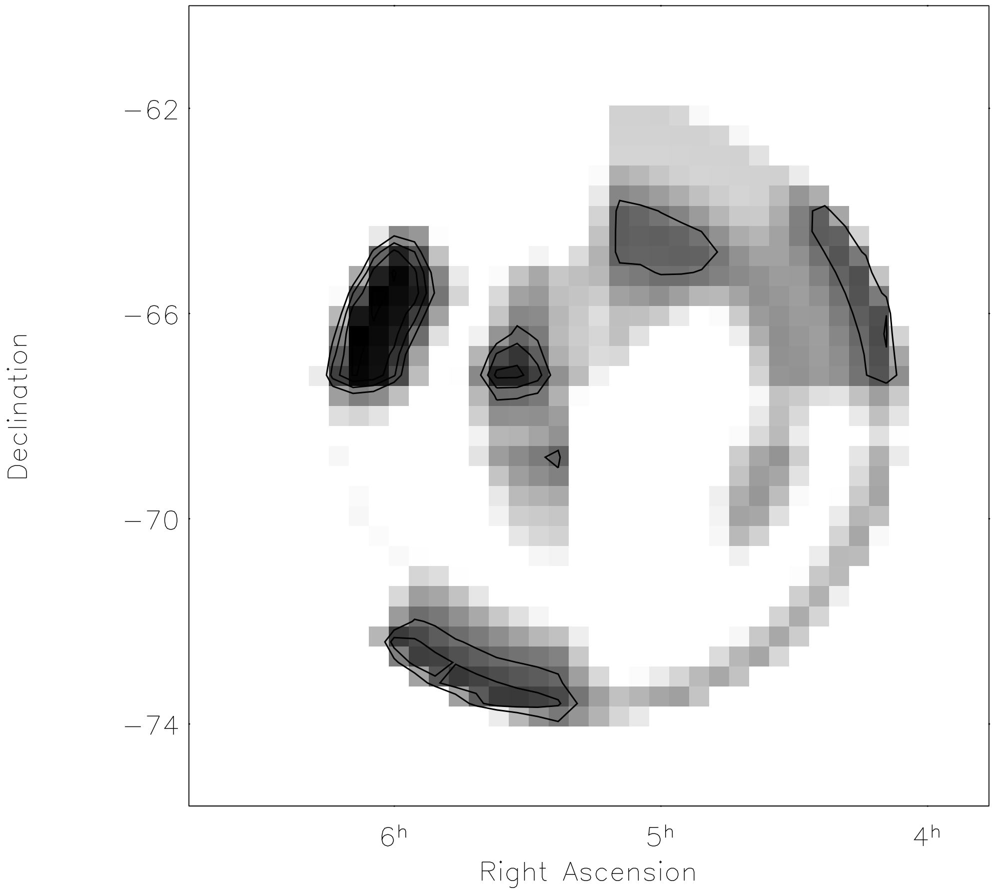

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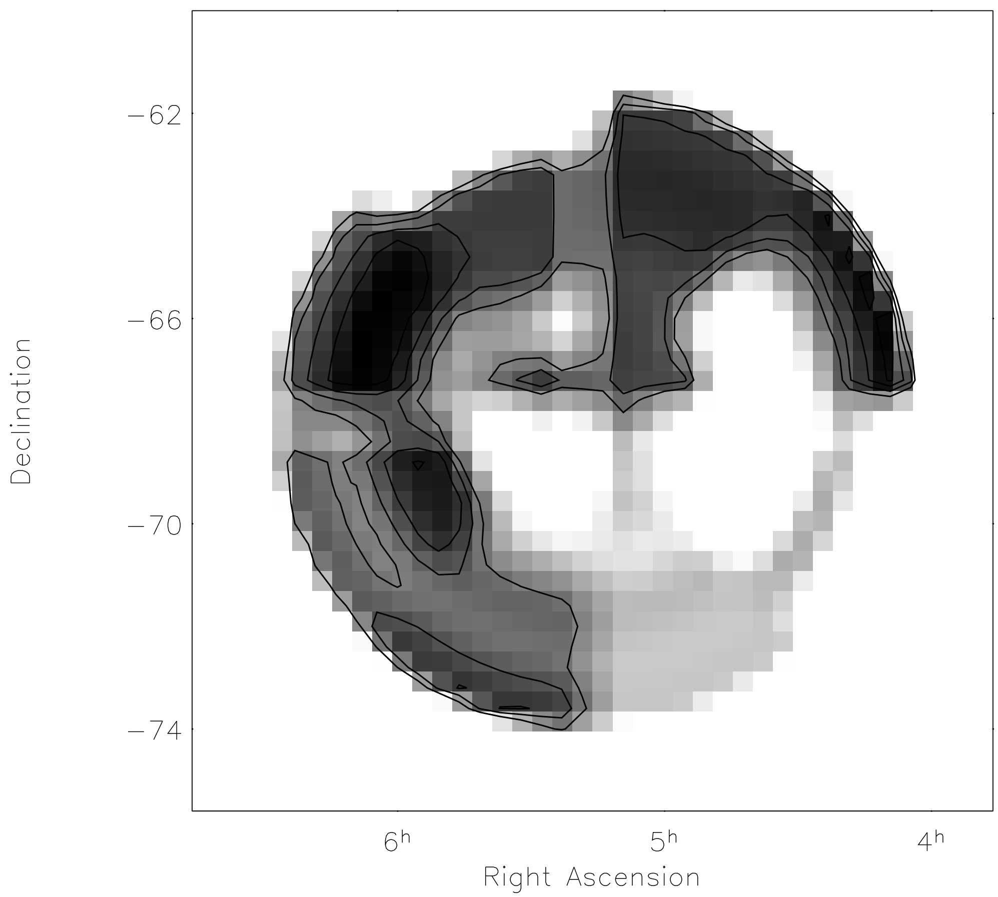

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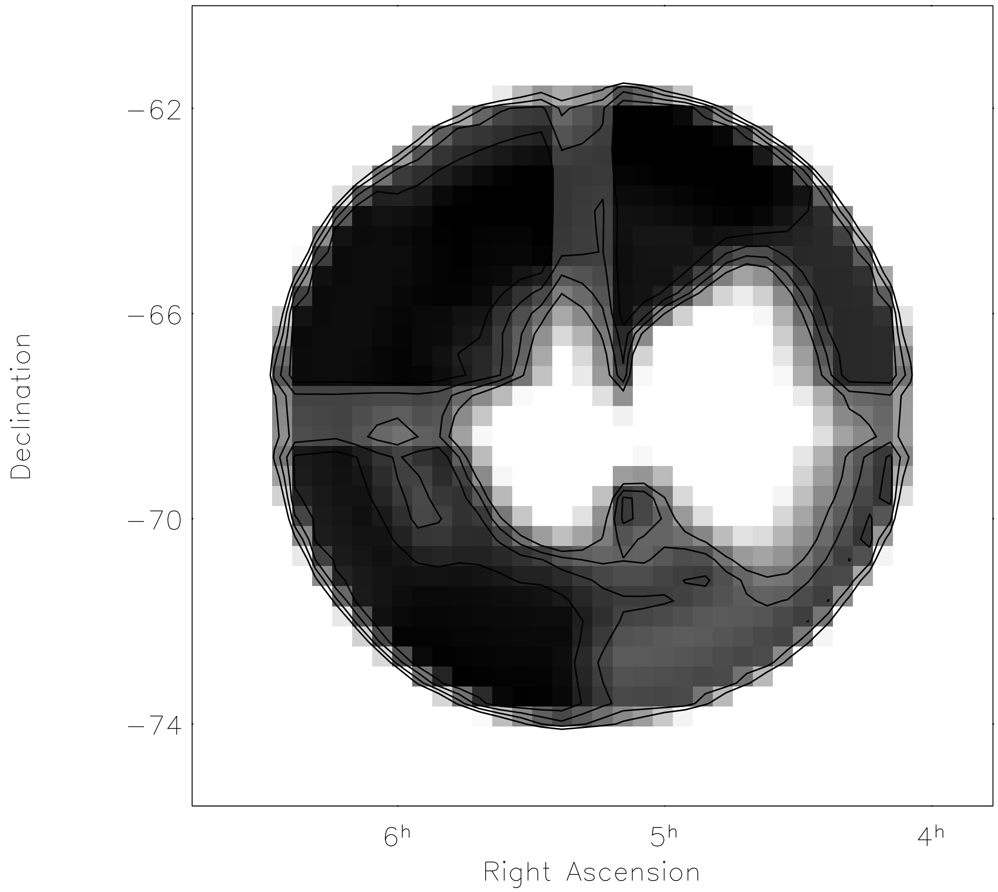
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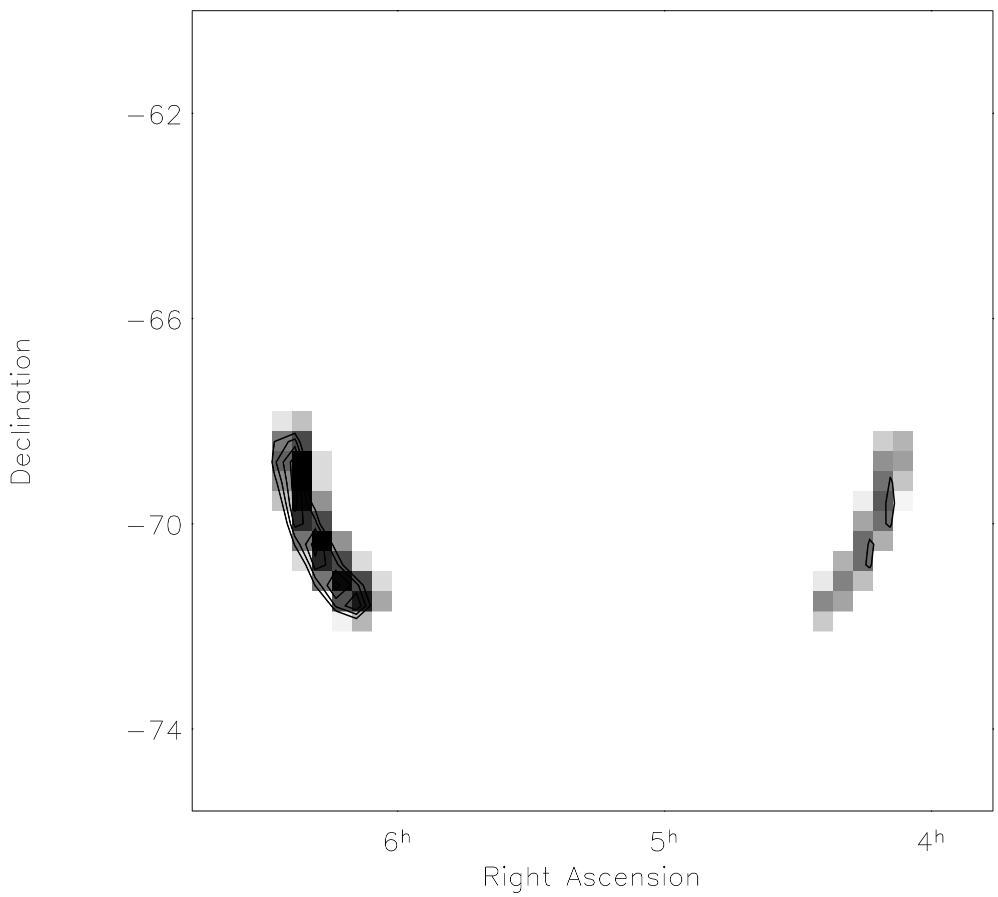

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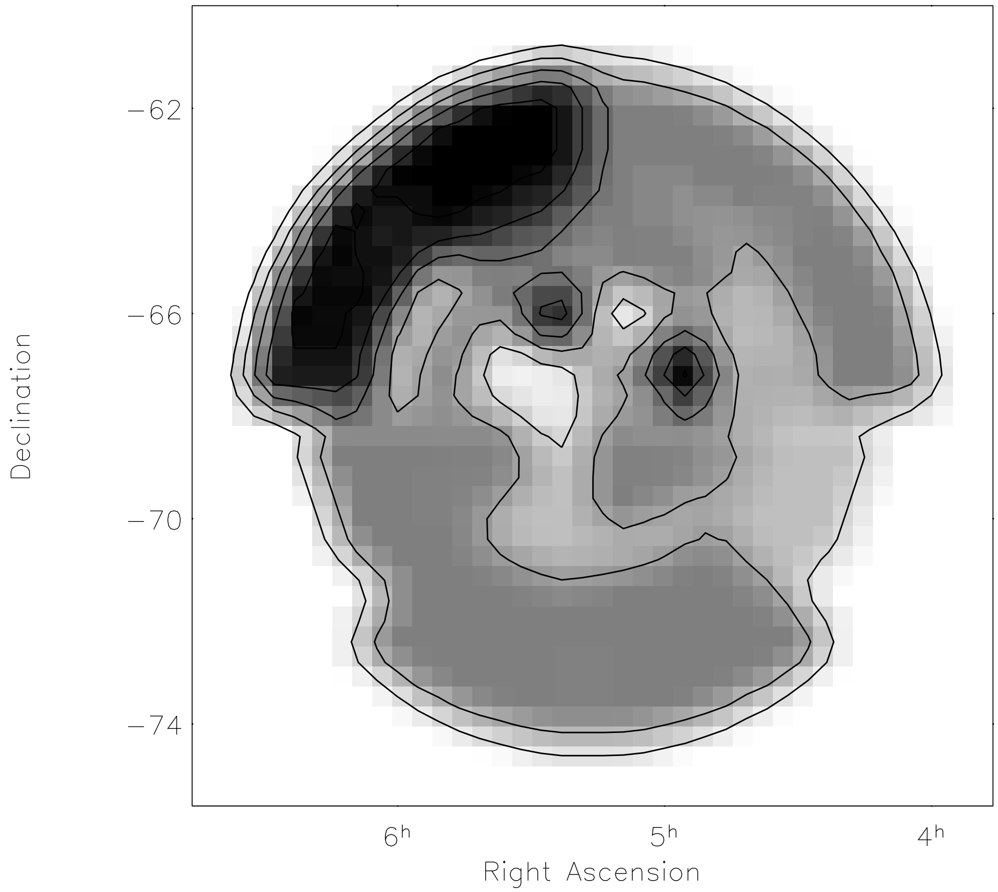

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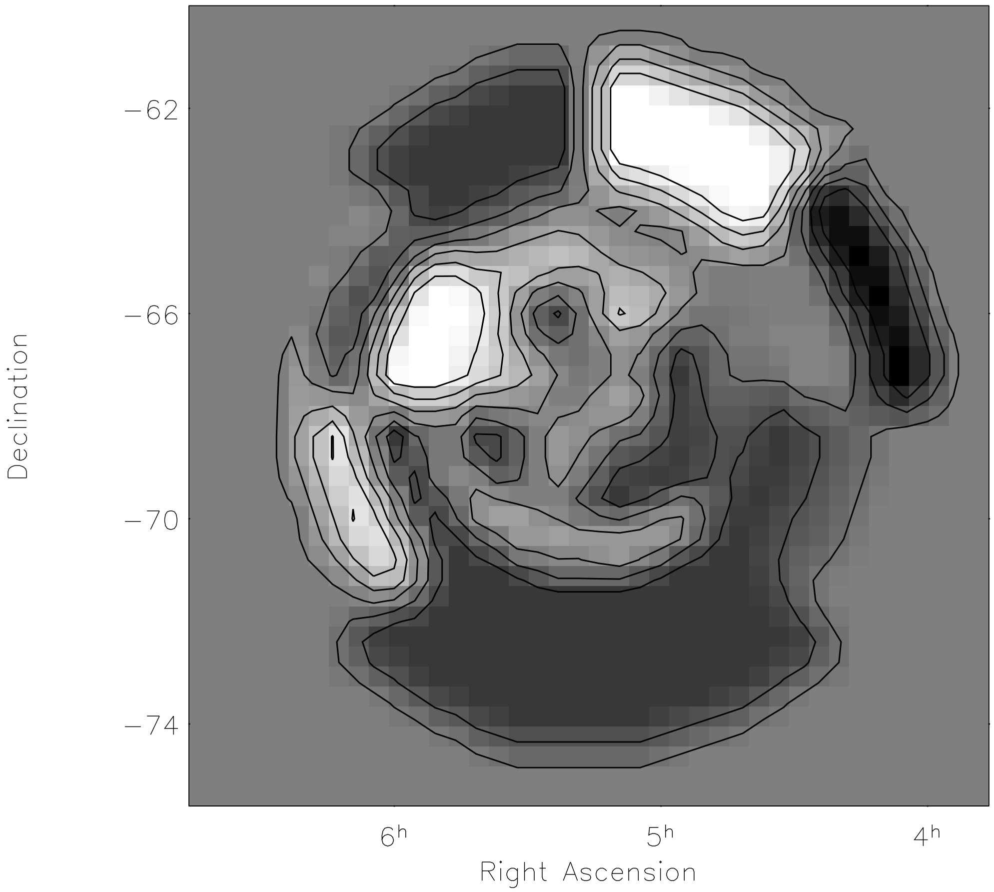

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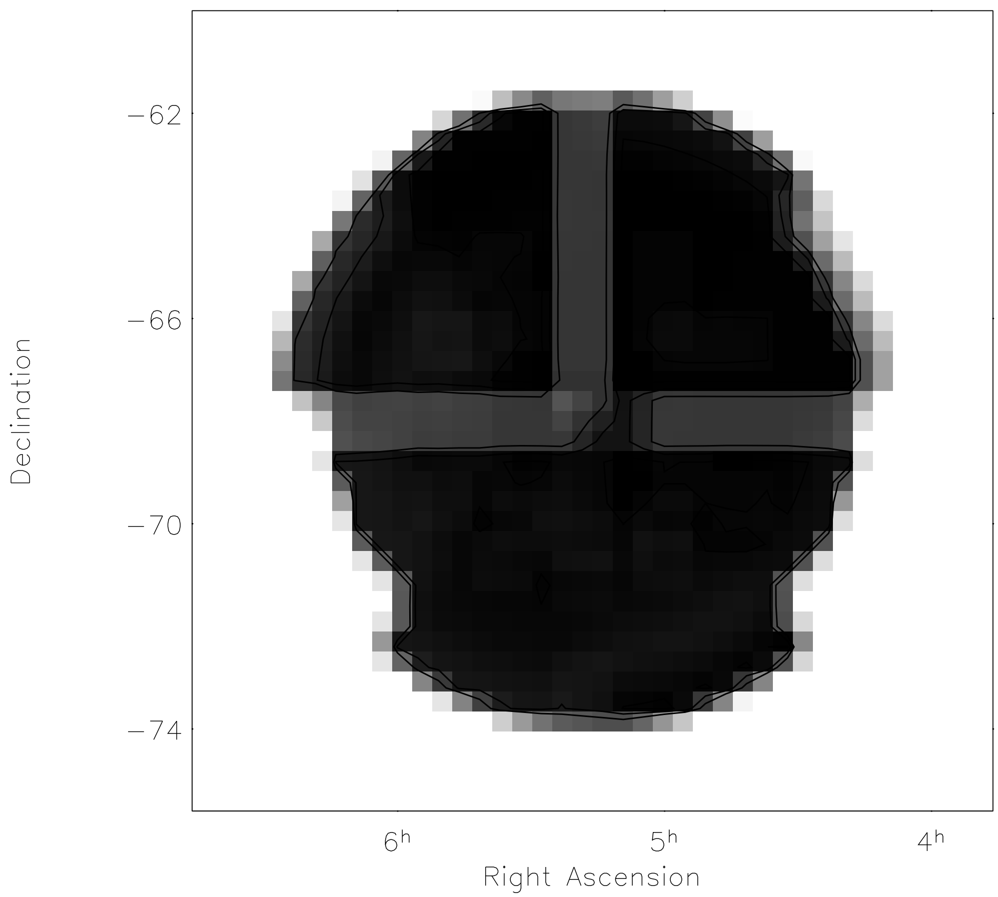

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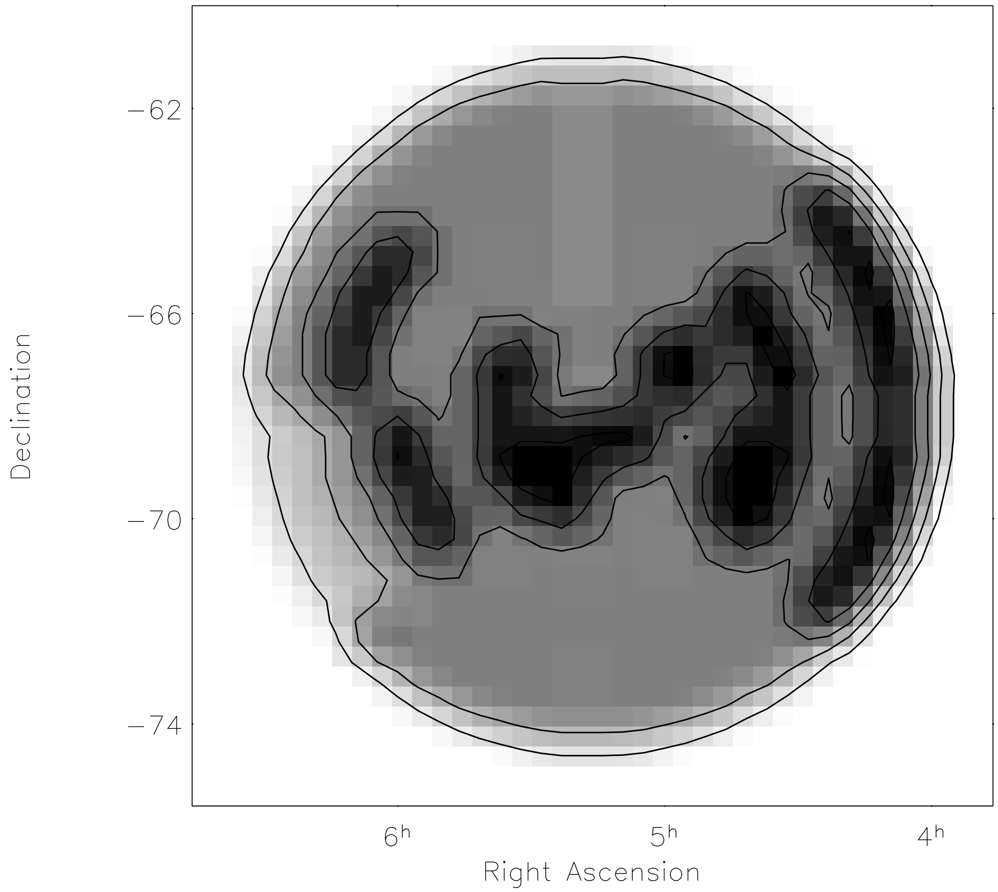

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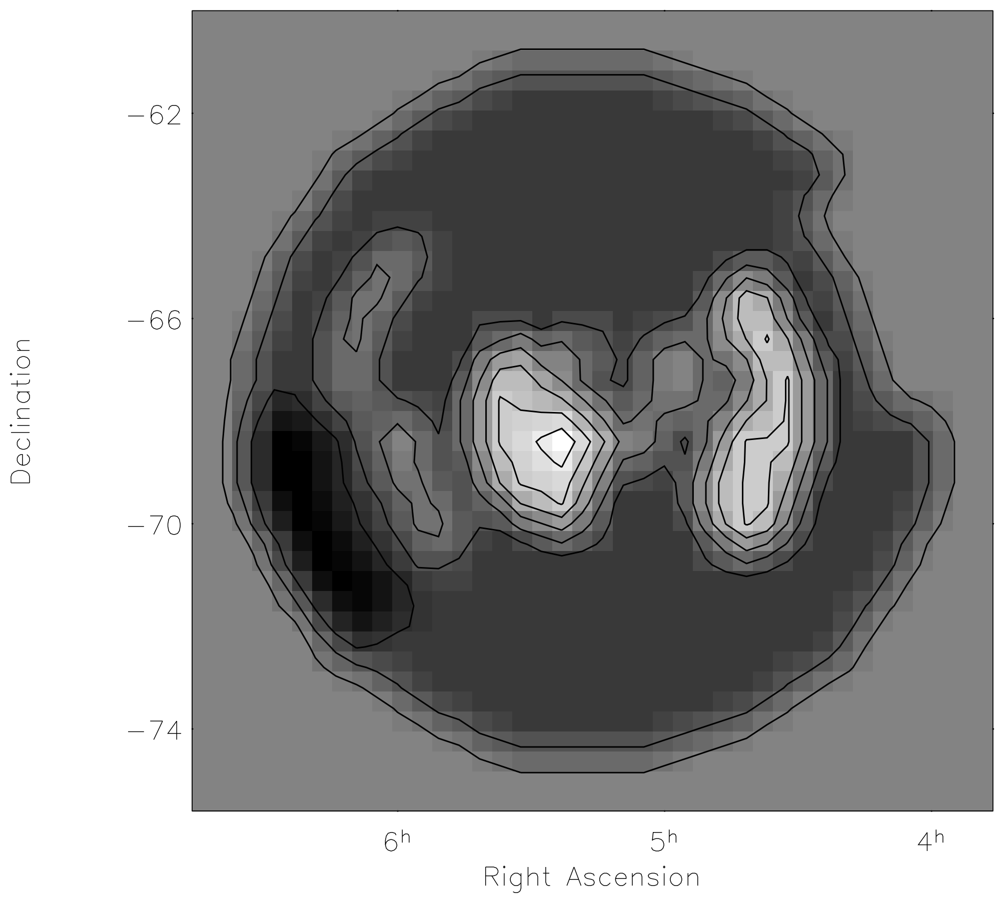

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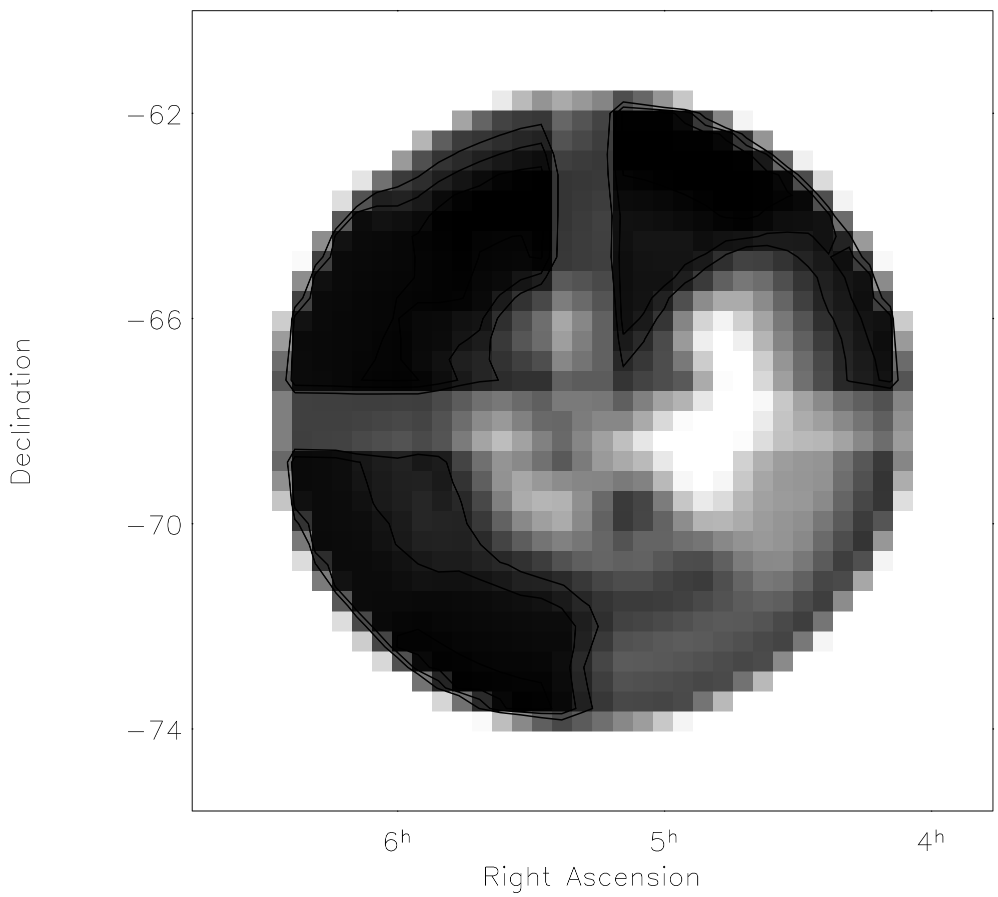

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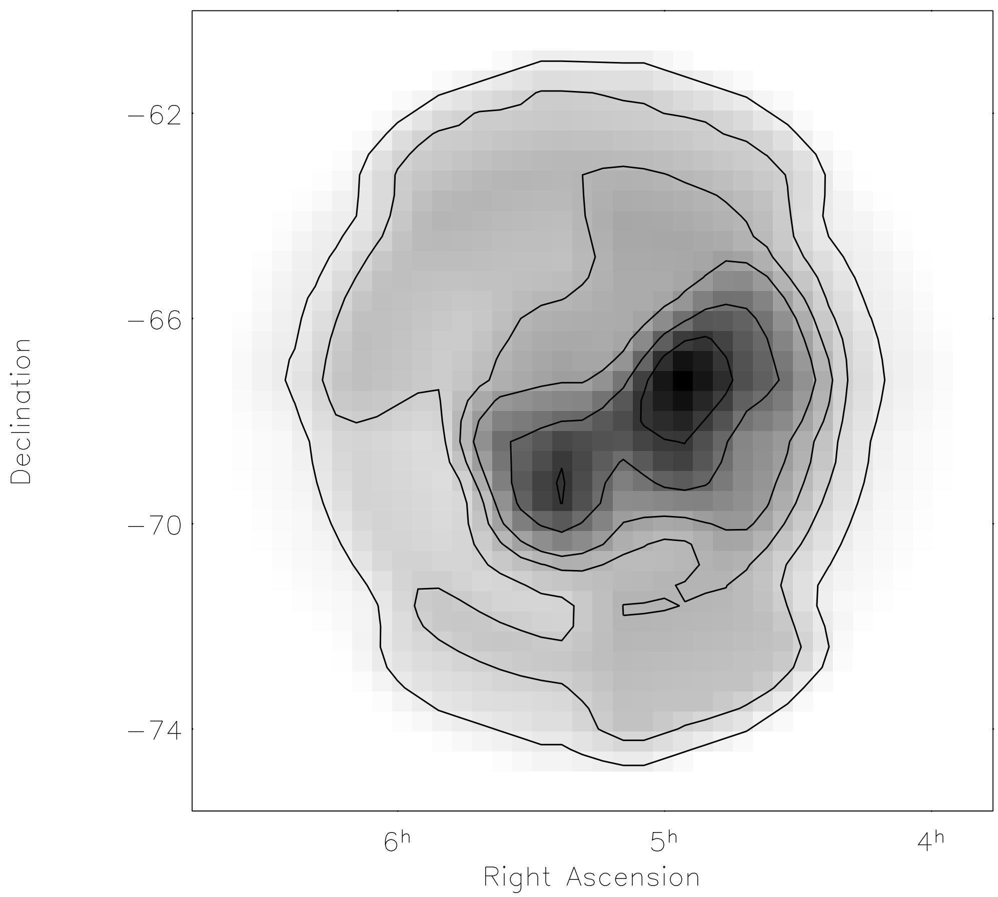
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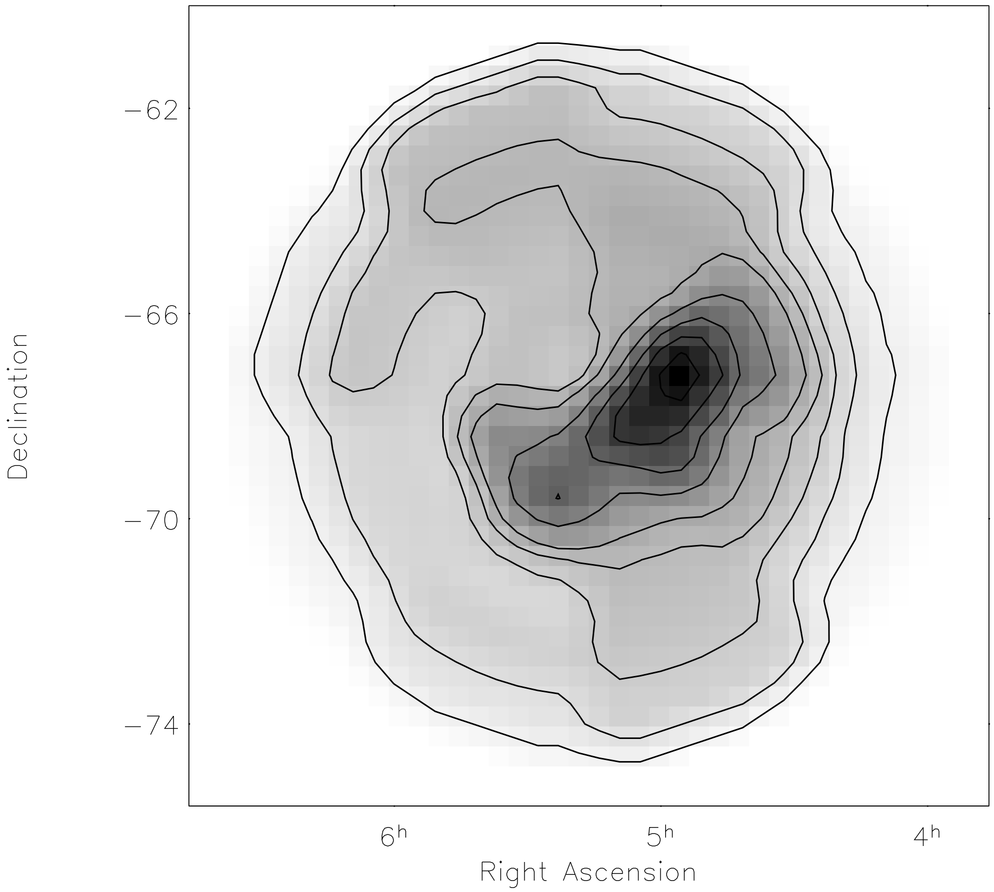
Right Ascension



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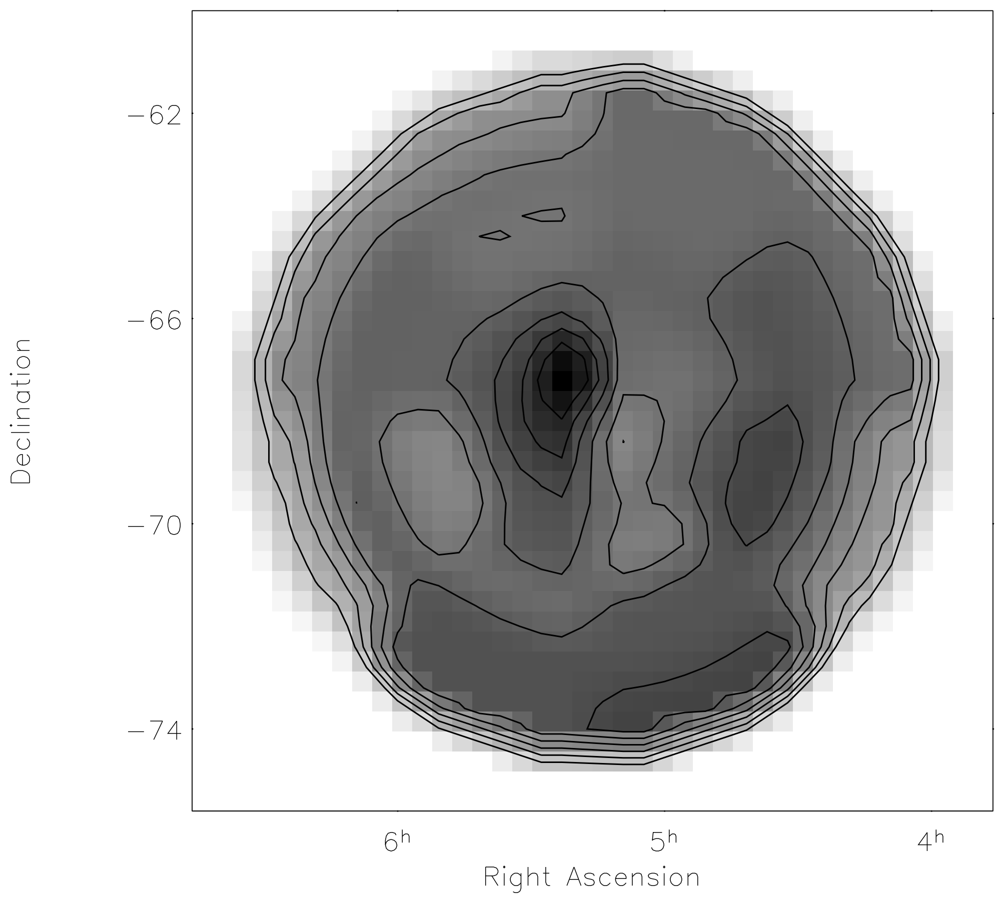

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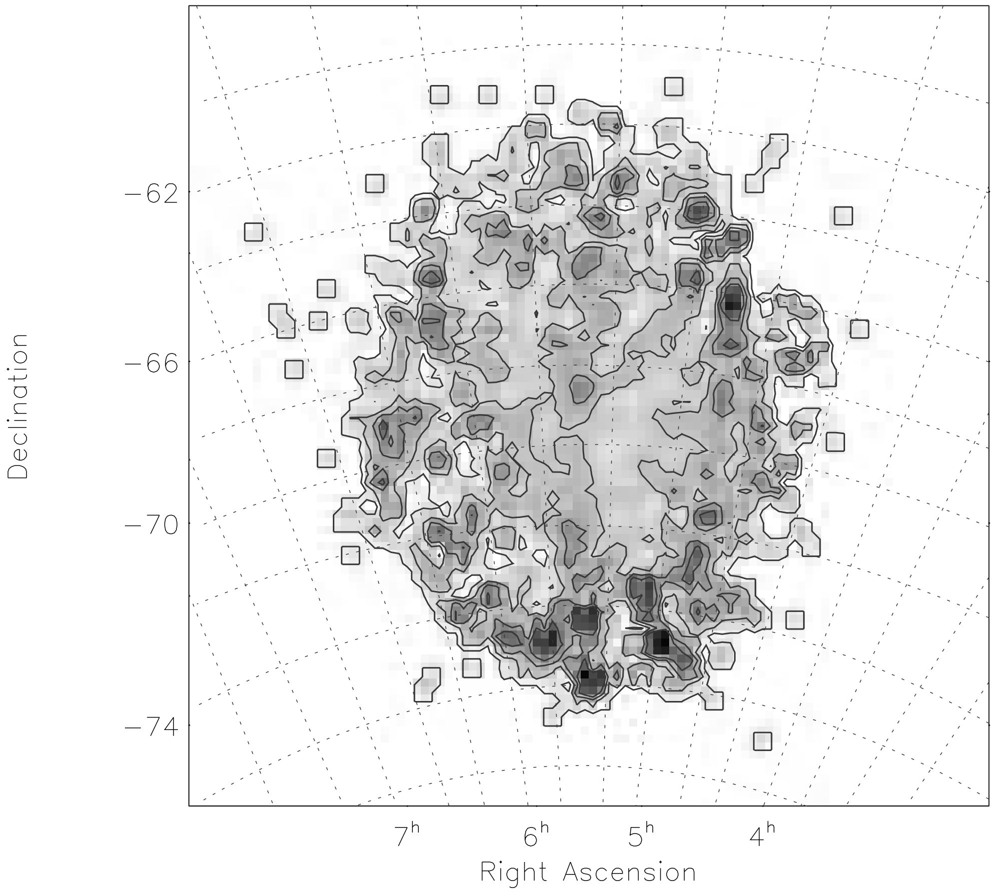

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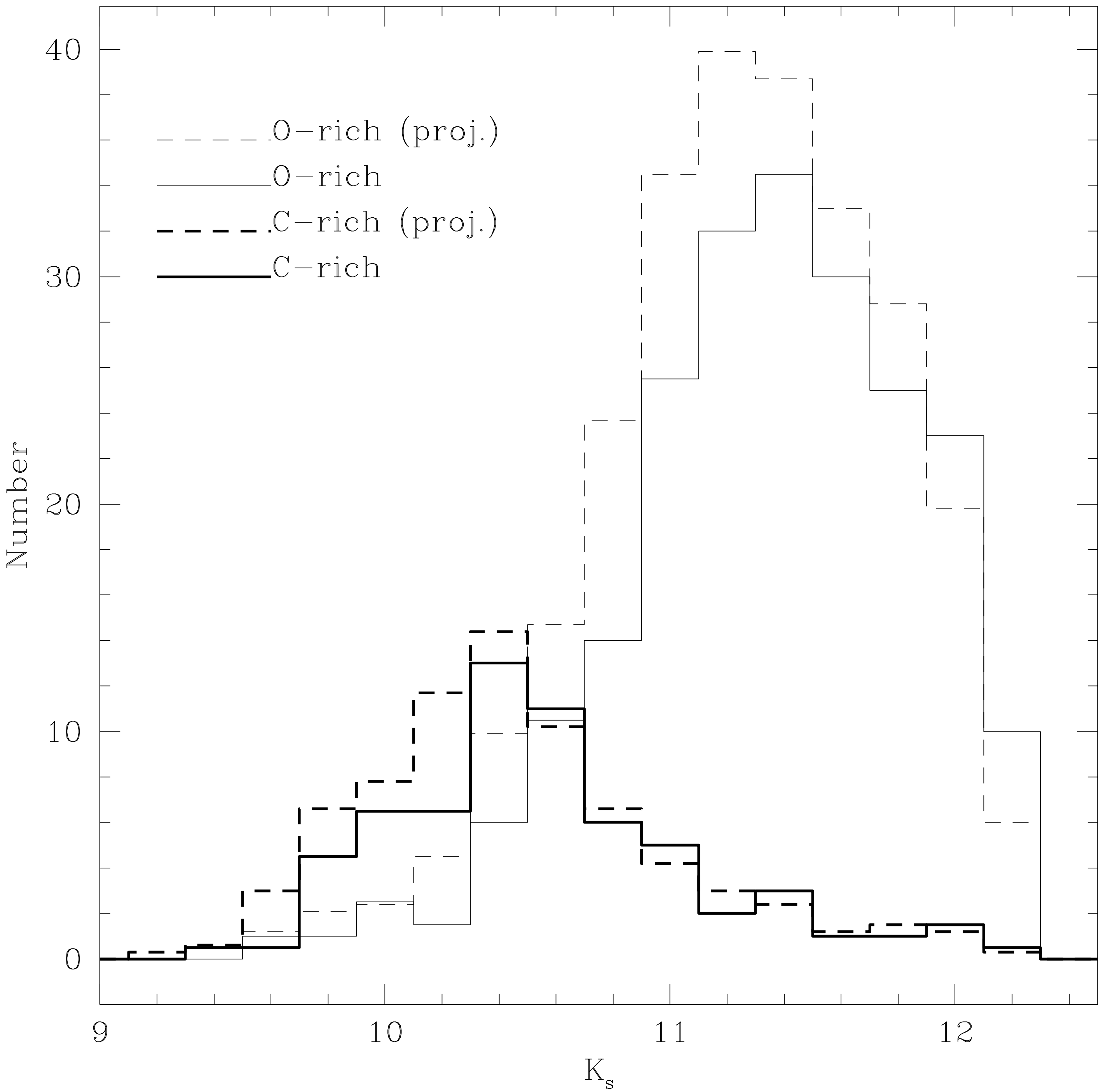
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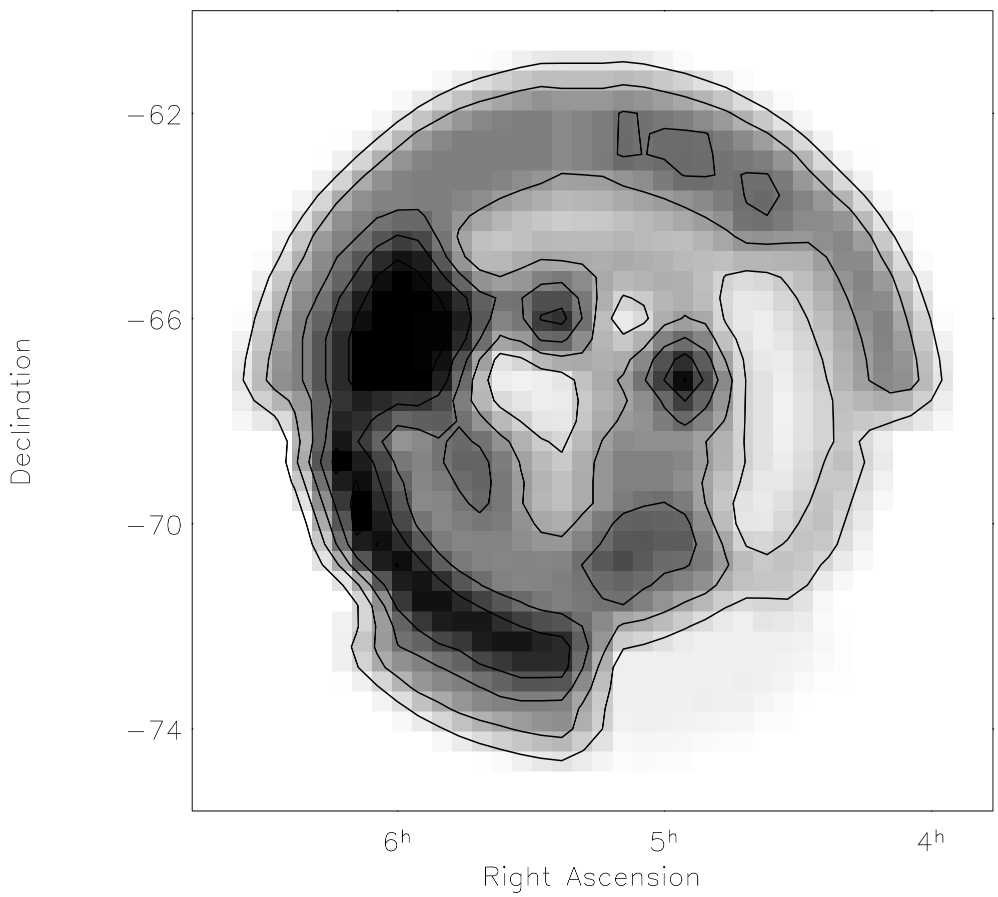

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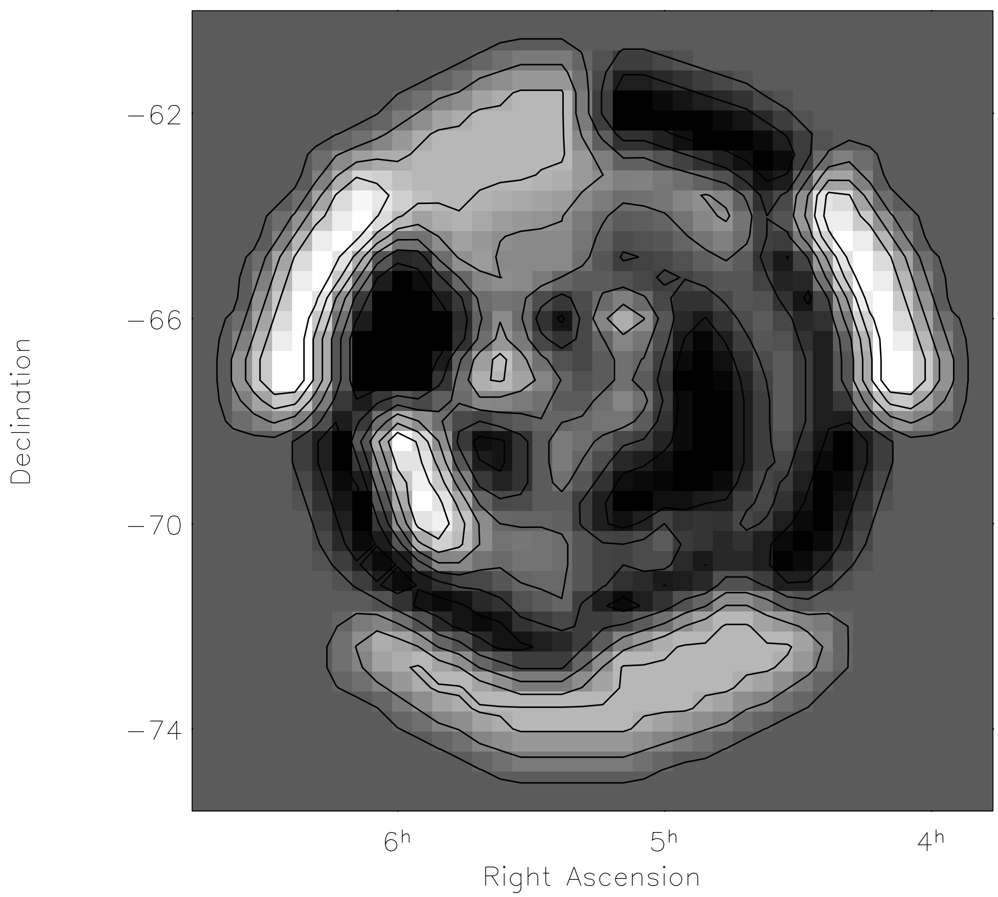
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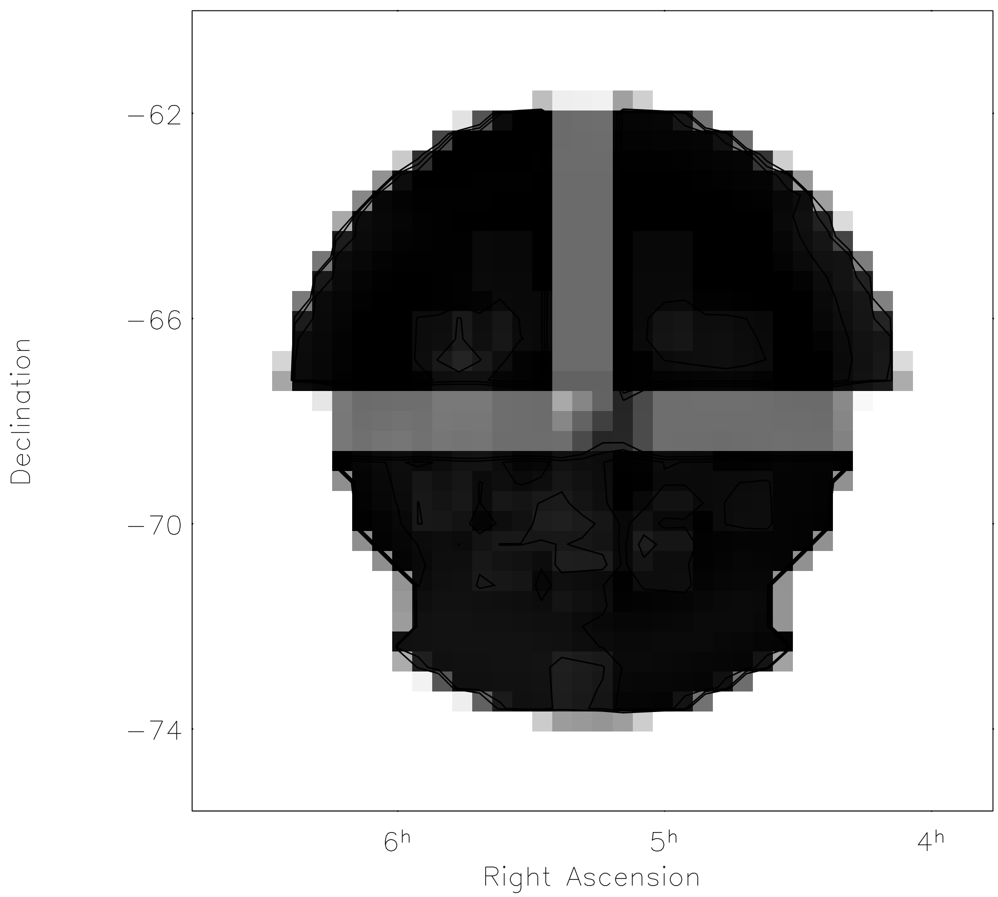

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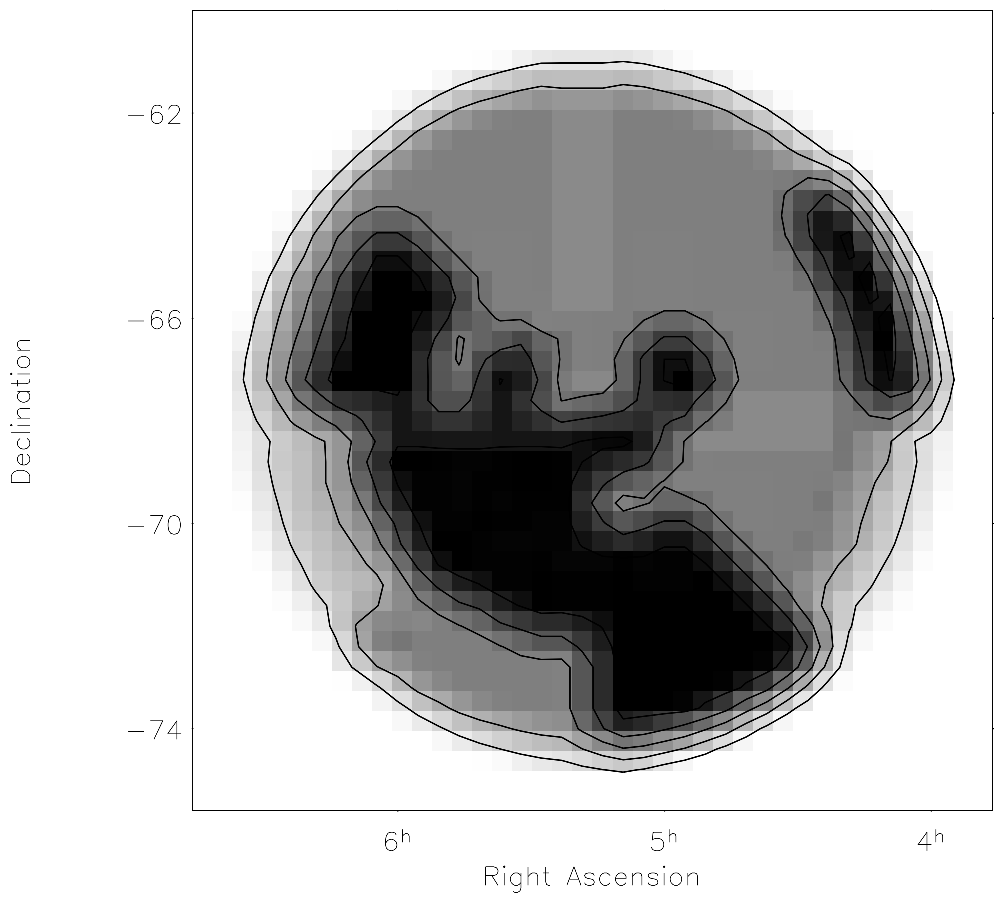

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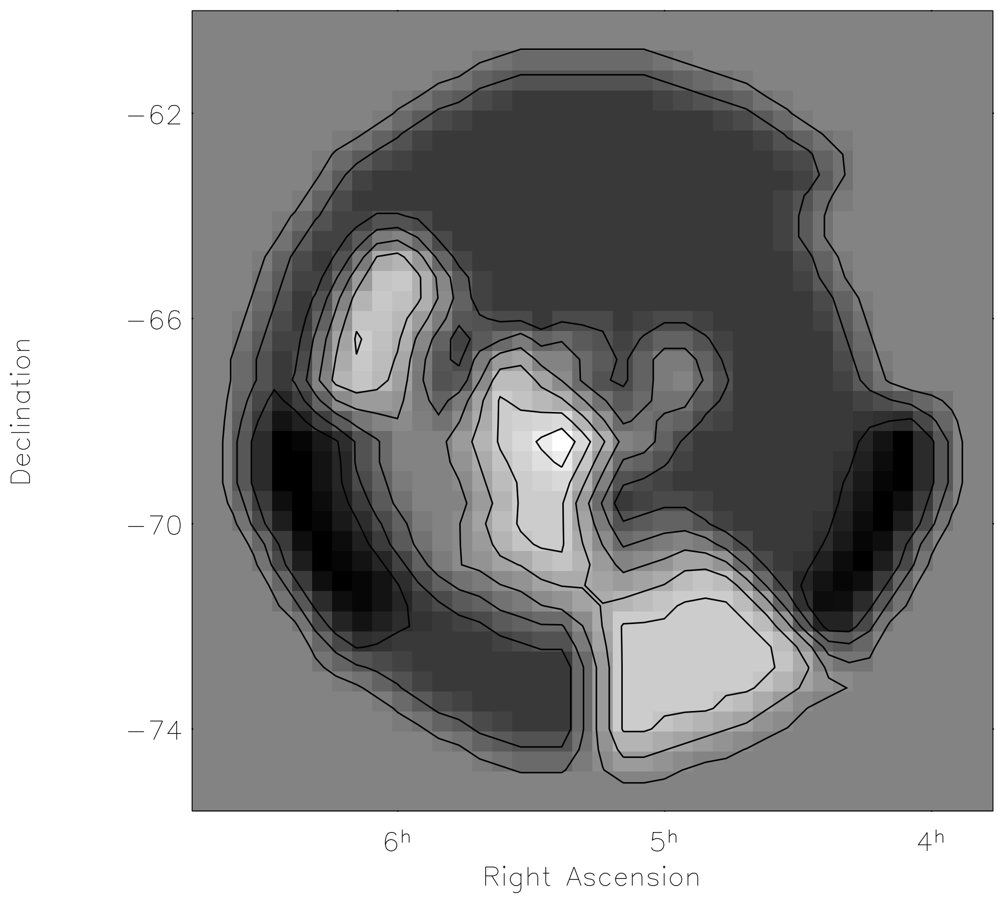
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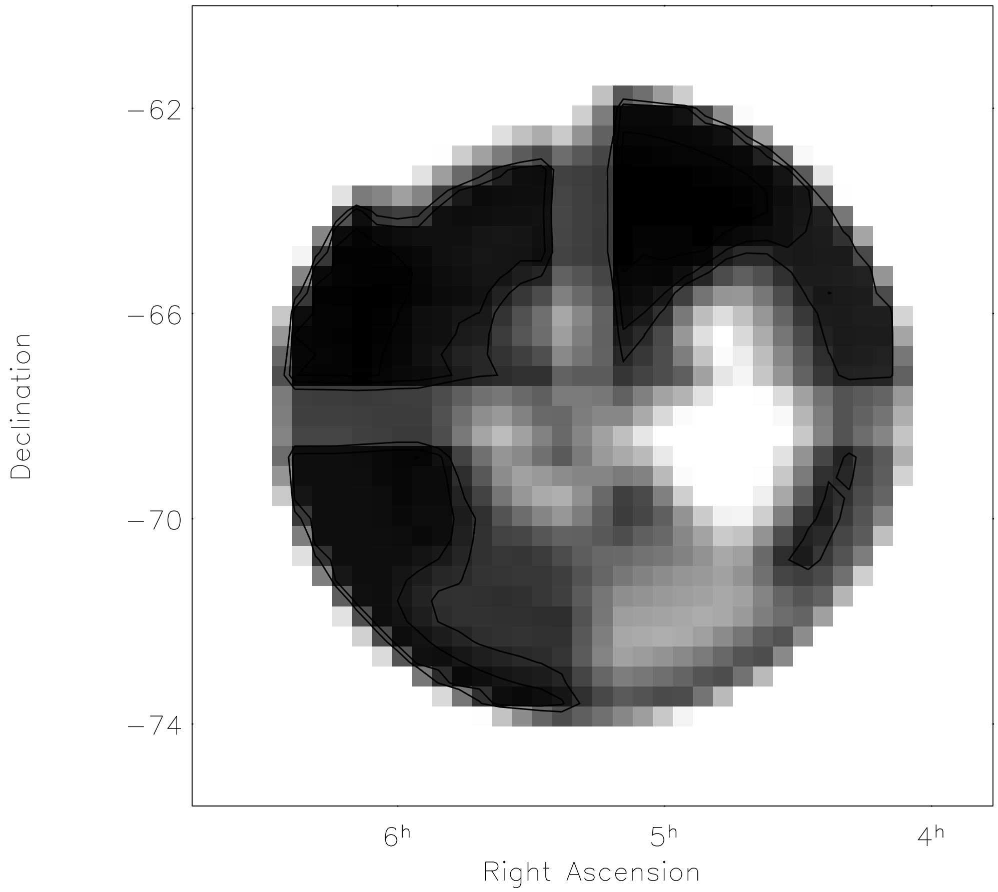

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