README for environmental masks **v5**

This is **version 5, released in July 2020**.

This document includes some frequently asked questions (FAQ) at the end.

Feedback is welcome! (m.querejeta@oan.es or miguelquerejeta@gmail.com)

Top directory- **<galaxy_name>_mask_v5.fits**: final environmental masks for each galaxy with additive labels (see below)
- **masks_v5_simple.tar.gz**: simple masks where each pixel is assigned to a single, dominant environment (~2MB compressed, ~700MB uncompressed)
- **masks_v5.tar.gz**: compressed version of final masks with additive labels (~2MB compressed, ~700MB uncompressed)
- **masks_v5_separate.tar.gz**: same as separate FITS for each component (e.g. NGC1300_mask_v5_bars.fits; ~6MB compressed, ~1.8GB uncompressed)
- **a_TABLE_Environmental_masks_v5**: spreadsheet listing components included for each galaxy, with quality flags (second tab = parameters that define masks).
- **a_PHANGS_catalog.pdf**: PDF catalog displaying multi-wavelength maps of the main PHANGS sample including environmental masks.
- README_Environmental_masks: this README file

Parameters
- PHANGS_masks_v4.dat: adopted parameters in ASCII format (missing=-999), to be uploaded soon; see **Origin of masks** below for the sources of these measurements. Same as second tab in TABLE_Environmental_masks
- Table_PHANGS_spiral_arms_parameters_v4.dat: table with the parameters adopted to construct spiral arm masks (log-spiral segments and widths)
- Buta+15_morph.dat: morphological classification that we adopt
- Herrera-Endoqui_ReadMe.txt: components for the following two tables
    - Herrera-Endoqui_table2.dat: bars, lenses, rings
    - Herrera-Endoqui_table3.dat: spiral arm segments
- JCMM_bars.dat: bars identified by Munoz-Mateos et al. (2013). In general, good agreement with the bars from Herrera-Endoqui; we decided to follow Herrera-Endoqui et al. (2015)
- Pipeline4_Table1.dat: S4G pipeline 4 (GALFIT): center and general params
- Pipeline4_Table8.dat: S4G pipeline 4: GALFIT photometric decompositions

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“Simple” masks: masks_v5_simple.tar.gz
For most purposes, it is likely simplest and sufficient to use these masks, where each pixel is assigned to one dominant environment. The following notation is used:

1 = center (small bulge, nuclear ring, nuclear disc, etc.)
2 = bar (excluding bar ends)
3 = bar ends (overlap of bar and spiral)
4 = interbar (R_gal < R_bar, but outside bar footprint)
5 = spiral arms inside interbar (R_gal < R_bar)
6 = spiral arms (R_gal > R_bar)
7 = interarm (only the R_gal spanned by spiral arms, and R_gal > R_bar)
8 = outer disc (R_gal > spiral arm ends, only for galaxies with identified spirals)
9 = interbar (“disc” where R_gal < R_bar) where no strong spiral arms were identified
10 = disc (R_gal > R_bar) where no spiral arms were identified (e.g. flocculent spirals)

For many purposes, the distinction between interarm and interbar (or bar vs bar ends) might not be important; in that case, the range of environments can be reduced to five:

1 = center
2 + 3 = bar
4 + 7 + 8 = interarm
5 + 6 = spiral arms
9 + 10 = disc in galaxies without spirals

Mask labels (full version with more information):
We have defined the environmental masks in such a way that a given pixel can be simultaneously assigned to multiple components (for example, a pixel can be part of the main exponential disk and also part of the bar). We use the following additive notation to assign morphological components to each pixel:

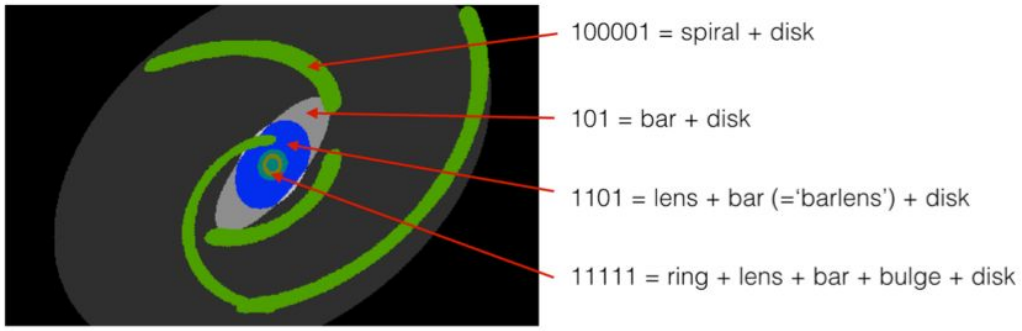
Disk = + 1 (if present, extra disk, e.g. inner disk = +2)
Bulge = + 10
Bar = + 100 (second bar, e.g. nuclear bar = +200)
Lens = + 1000 (second lens = +2000)
Ring = + 10000 (second ring = +20000, third ring = +30000)
Spiral arms = +100000
Center = +1000000

e.g. 111 = pixel belongs to: bar, bulge, disk
101 = pixel belongs to: bar, disk
10101 = pixel belongs to: ring, bar, disk

Thus, a pixel labelled 101 belongs simultaneously to the main disk and the bar. There can also be two distinct disks (e.g. due to a radial truncation: two different exponential profiles), in which case +2 will correspond to the inner disk, and +1 to the outer disk; the same applies to nuclear bars, which will correspond to +200 on top of the large-scale bar which is +100.

When multiple rings exist, they are subsequently identified as +10000, +20000, +30000. The individual spiral arm segments are also given sequential numbers (+100000, +200000, etc.).

Illustrative example:



There are multiple strategies to extract one of these components. Some examples in IDL:

- Select the disk (out to 2*Re):
  mask GE 1
- Select the bar (+100, i.e. third digit from the end =1)
  STRMID(STRING(mask),2,1,/REVERSE_OFFSET) EQ '1'
  or: (FLOOR(mask/100.)-10*FLOOR(mask/1000.)) EQ 1

Alternatively, the file **Separate_components.tar.gz** includes individual FITS files for each type of component (note that, when uncompressed, all the files take ~2GB):

<galaxy_name>_mask_v5_P4.fits ==> exp disk(s) + Sersic bulge (S4G pipeline 4)
<galaxy_name>_mask_v5_bars.fits ==> bar (+ in a few cases nuclear bar)
<galaxy_name>_mask_v5_lenses.fits ==> lenses
<galaxy_name>_mask_v5_rings.fits ==> rings
<galaxy_name>_mask_v5_sp_arms.fits ==> spiral arms

(!) Important note on duplicates:

"***Bulges***" are identified in GALFIT decompositions that do not account for rings, but very often they are just the extra light coming from a nuclear ring (example: NGC1300). These cases are marked in a_TABLE_Environmental_masks_v4.xlsx (tab='Components', column='Comments'). More details below under *Origin of masks: b) Bulges*.

"***Barlenses***" should probably be considered for most purposes as part of the bar (more details below under *Origin of masks: c) Bars*). These PHANGS galaxies have a barlens (as Lens_1, ID=1000… but not all Lens_1 are barlenses!): NGC 1097, 1300, 1512, 2566, 3351, 4548, 4579, 5134, 5643, 6300.

Origin of masks:

a) Disk(s): from S4G pipeline 4 (GALFIT). We define the edge of the exponential disk as twice the effective radius. Sometimes, two distinct exponential disks were fitted with GALFIT; in that case, we keep both in the masks (region +1 and +2).

b) Bulge(s): from S4G pipeline 4 (GALFIT). Outer edge defined as twice the effective radius. Note: galaxies outside S4G do not have disk masks yet, but we will also try to add those.

- we removed the bulges in IC5332, NGC5584 because of questionable orientation or redundant with a bar

IMPORTANT NOTE on BULGE vs RING: Very often a "***bulge***" coincides with a "***nuclear ring***" (example: NGC1300). We keep both components, bulge and nuclear ring, because depending on the purpose one may want to flag the whole area (the generic 'bulge') or be more specific and identify the annular region corresponding to the resonant ring. In any case, the bulge in most of these cases is probably the result of GALFIT trying to find the best photometric model fitting a Sersic profile (rings were not modelled as such with GALFIT --which is why their excess flux is often recognised as bulges). These cases are marked in a_TABLE_Environmental_masks_v4.xlsx (tab='Components', column='Comments')

c) Bar(s): mostly from Herrera-Endoqui et al. (2015). These are visually identified bars, and their quality is notably higher than using the results from S4G pipeline 4 (GALFIT). Ref column indicates origin galaxy by galaxy:

1=Herrera-Endoqui et al. (2015);
2=Menéndez-Delmestre et al. (2007);
3=Querejeta et al. (in prep.);
4=Martin (1995) - questionable!

Quality flags:

1 = best quality;
2 = bar parameters not so clear;
4 = not completely clear if this is a bar

Details: We rely on all clear bars with Quality Flag=1 from Herrera-Endoqui et al. (2015), but made the following modifications:

- *removed the bar* in IC5332, NGC1546 (unclear)
- *kept the bar but decreased quality flag* to 2 in:
  NGC0685, NGC1087, IC1954,NGC4540
- *added the following bars*, which we consider important even if they are somewhat hard to define (and we therefore keep Quality Flag=2):
  NGC1559, NGC3511,NGC4496A,NGC4569,NGC4654,
  NGC4731,NGC4781,NGC5068
- *redefined the following bars* (using a different centre from S4G P4 + new shape):
  NGC1511, NGC1559, NGC4424, IC1954

- *for galaxies outside S4G*, we adopted some measurements from the literature when available and measured the bar size and orientation on Spitzer 3.6um images in the remaining cases:

NGC1317: inner and outer bar from Erwin (2004)

NGC2566: measured here; adopted bar length is a compromise solution between Laine+02, Laurikainen+04b, Marinova+06.

NGC2997: bar length and ellipticity from Martin (1995), in good agreement with new visual estimate on 3.6um images; PA measured here.

NGC5643: bar length, PA, ellipticity from Menéndez-Delmestre et al. (2007)

NGC6300: bar length, PA, ellipticity from Menéndez-Delmestre et al. (2007)

NGC6744: bar length, PA, ellipticity from Menéndez-Delmestre et al. (2007)

IMPORTANT NOTE on BARLENSES: "***Barlenses***" are lens-like structures embedded in bars (typically spanning ~50% of the bar size). Their surface brightness drops fast at the edges. Unlike other lenses, they are thought to be the face-on counterparts of the vertically thick boxy/peanut structures of bars (see Laurikainen et al. 2011; Laurikainen et al. 2014; Athanassoula et al. 2014; Laurikainen & Salo 2015). Therefore, for most purposes, they can be considered part of the bar and should be masked together (unless one is willing to specifically isolate these kinds of structures, which are prominent only in *some* bars). Environmental masks with barlens (as Lens_1, ID=1000… but not all Lens_1 are barlenses!):

NGC1097, *NGC1300, NGC1512, NGC2566, NGC3351, NGC4548, NGC4579, NGC5134, NGC5643, NGC6300.*

These identifications come from Herrera-Endoqui et al. (2015), except for galaxies outside S4G (NGC2566, NGC5643, NGC6300); in those cases, these are new identifications (Querejeta et al. in prep.).

d) Lens(es): from Herrera-Endoqui et al. (2015). Only those with best quality flag (Flag=2). This includes lenses, barlenses, ringlenses. For galaxies outside S4G, we measured the size and orientation of lenses on Spitzer IRAC 3.6um images.

e) Ring(s): from Herrera-Endoqui et al. (2015). Only those with best quality flag (Flag=2), avoiding pseudo-rings (no R', r', rs, nr', etc.). We defined the width by eye on IRAC1 images, varying contrast and drawing ellipses to mark the edge. We removed the nuclear ring in NGC4536, as we found it impossible to define an inner edge. For galaxies outside S4G, we measured the size and orientation of rings on Spitzer IRAC 3.6um images.

f) Spiral arms: analytic log-spiral segments fitted to bright points marked by eye on unsharp-masked Spitzer IRAC 3.6um images; width assigned to optimise overlap with CO. Most of the analytic segments for S4G galaxies come from Herrera-Endoqui et al. (2015), although we fitted some more when we felt that important spiral arm parts were missing, and removed the ones that looked less robust. For galaxies outside S4G, we performed new fits on unsharp-masked Spitzer IRAC 3.6um maps, following a strategy analogous to Herrera-Endoqui et al. (2015). See some details on masks for specific galaxies below.

g) Centers: a new category (not present in v4) developed for Jiayi's letter to account for special features in the nuclei of many galaxies (particularly barred galaxies) that are not resolved by the *Spitzer* IRAC images (or barely resolved). These could be reflecting e.g. unresolved nuclear rings; we are not able to define the actual ring, but we delimit the area where there seems to be some excess light. These can complement the "bulge" category, that for small nuclear structures often covers similarly unresolved excess light. These centers often correspond to a "nucleus PSF" in the S4G photometric decompositions.

Detailed strategy to make (simple) 2D masks for spiral arms:

1) For each analytic log-spiral segment, construct a set of dilated masks varying the width (500pc, 1000pc, 1500pc, ..., 3000pc).
2) Measure total CO flux (on the ALMA-7m moment-0 map) contained in each of the masks (width1=500pc, width2=1000pc, width3=1500pc, etc.).
3) Take ratio of flux from one mask to the next: CO(width2) / CO(width1), CO(width3) / CO(width2), etc.
4) Final width is set where the ratio CO(widthN) / CO(widthN-1) falls below an (empirical) threshold of 1.25 (i.e. the flux increases by less than 25% from one step to the next). This empirical convergence criterion results in spiral masks which are typically ~1-2 kpc wide and capture most of the 3.6um, CO, and Halpha arm region.

When the overlap between a given dilated spiral segment and the CO map is low (<30% of 3.6um spiral has CO coverage from ALMA 7m), the width is set as the average of the CO widths for any other spiral arms in that same galaxy. These cases are indicated in a table listing the analytic parameters for the spiral masks, which will be released soon.

We decided on the endpoints of each arm segment (i.e. start and finish azimuth of the log-spiral) through visual inspection, on a case-by-case basis, in order to: a) provide continuity along coherent arms when there is a change in pitch angle (i.e. two or more segments trace a given arm); b) capture the spiral arm structures in 3.6um, CO, and Halpha as well as possible towards the inner and outer ends along the arms.

Three members of the working group (Eva, Sharon, Miguel) performed two rounds of quality flagging, re-adjusting the start/finish azimuth of some segments, modifying the width in a few cases where the empirical CO criterion failed, and removing any segments that we considered were not robust enough. The decision to keep only the more significant spiral segments implies that, in many galaxies (mostly flocculent and some multi-armed cases), we removed the spiral mask completely. The masks for those missing cases and less reliable segments in other masks are available from Miguel upon request (m.querejeta@oan.es or miguelquerejeta@gmail.com), but we emphasise that these should be used with extreme caution.

Notes for specific galaxies:

NGC0628: the central part of the galaxy (R<~23") is identified as bulge. This innermost part also shows spiral structure in CO, with an abrupt change of pitch angle, but these inner spiral arms do not stand out in NIR and are not captured by the mask
NGC1097: spiral arms cover the bar end region (there is a small overlap between the spiral and bar mask, either or both can be selected depending on the specific goal)
NGC1385: the spiral arms are not very prominent
NGC1512: the spiral arms are tightly wound, and they can be seen as ring (masks includes both spiral and ring identification, user can decide for either or both of them depending on specific goal)
NGC1637: there is some ambiguity regarding the number of arms (there is a dominant bisymmetric *m*=2 mode, whereas the third arm is clearly fainter; it is up to the user whether to keep the southern arm or not).
NGC2566: spiral is not symmetric.
NGC4254: northern spiral segment is less strong than the others, it is up to the user whether to include it or not.
NGC4321: easternmost spiral segment is less strong than the others, it is up to the user whether to include it or not.
NGC4536: easternmost spiral segment is not very prominent.
NGC4548: the two innermost spiral segments extend beyond the bar ends, similar to a ring; it is up to the user whether to include these segments as part of the spiral arms or not. The outermost western spiral arm is not very prominent.
NGC5248: current mask does not cover innermost spiral structure.

Future improvements

a) We will consider building more sophisticated masks distinguishing parts of bars (e.g. bar lanes, bar ends) and substructures within arm and interarm region for some of the best cases.
b) We will try to extend the strategy of these environmental masks to other PHANGS-like galaxies outside the canonical PHANGS sample of 74 galaxies (e.g. including IC342 and other nearby targets with good molecular data).

FAQ:

*What is the **latest version** of the masks and where can I find it?*

Since summer 2020, the latest version is **v5**. Since Jan 2020, it's available under /PHANGS/Archive/Products/environmental_masks/v5 (before, they were available under /scratch/Environmental_masks).

*What **format** do the masks have?*

They are FITS files (2D), with a simple version that assigns each pixel to a dominant environment under masks_v5_simple.tar.gz. The notation is explained below and in the header; for most applications, the labels can be combined such that **1 =** center; **2** & **3 =** bar; **4** & **7** & **8 =** interarm; **5** & **6 =** spiral arms; **9 =** disc in galaxies without spirals.

A more extensive version, <galaxy_name>_mask_v5.fits (also compressed as masks_v5.tar.gz) uses positional notation (last digit=disc; former-to-last=bulge; previous digit=bar; etc.) to allow to extract overlapping environments (e.g. a nuclear ring is often part of a bar simultaneously). An alternative to this notation with as many independent FITS files as environments is also available (but beware this is ~6MB compressed, ~1.8GB uncompressed): masks_v5_separate.tar.gz.

*What **paper** should I cite and how can I briefly describe the masks?*

The masks are described in **Querejeta et al. (in prep.)**. An example of a short explanation for the masks (to be adapted depending on what environments are used):

We study the environmental dependence based on morphological regions identified on near-infrared (NIR) images. The construction of these environmental masks is explained in detail in Querejeta et al. (in prep). In brief, discs and bulges are identified via 2D photometric decompositions of \textit{Spitzer} IRAC 3.6\,μm images. The size and orientation of bars and rings are defined visually on the NIR images. Finally, spiral arms are only explicitly included when they strongly dominante the galaxy disc (excluding rather flocculent spirals). Specifically, a log-spiral function is fitted to bright regions along arms on the NIR images, and assigned a width determined empirically based on CO emission. For galaxies in the \textit{Spitzer} Survey of Stellar Structure in Galaxies (S^{4}G), we mostly follow Salo et al.\ (2015) and Herrera-Endoqui et al.\ (2015). For the remaining galaxies, we rely on measurements from the literature and new fits to IRAC 3.6\,μm images.

*Why does my **spiral** galaxy not have a spiral mask?*

After a long discussion, we decided to keep spiral masks only when they trace well-delineated spiral arms that can be followed across most of the galaxy disc. As we move to more multi-armed/flocculent spirals, the distinction between arm and interarm becomes increasingly arbitrary, so the masks would not be as robust. Some of these less reliable

spiral masks can still be obtained upon request if you are particularly interested (m.querejeta@oan.es).

*Why should I **avoid the word "bulge"**?*

Photometric decompositions often distinguish an exponential disc from a more concentrated central component traditionally named "bulge". We include this "bulge" component in the masks inherited from such photometric decompositions (e.g. GALFIT on S4G, Salo et al. 2015). However, these GALFIT decompositions did not explicitly account for inner structures such as nuclear rings or nuclear discs, and the bulge component often reflects rings and other nuclear structures. In fact, we now think that most of these small bulges are likely rather flat structures that do not "bulge out" of the disc (e.g. pseudobulges), and which are far from spheroidal components they were once thought to be. In general, we recommend avoiding the word "bulge" and grouping such nuclear components under the deliberately more generic label of "centres".