Gravitational Potential Core Identification User's Guide

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1. Introduction

GRID-core (Gravitational potential Identification of cores) is a core-finding method using the contours of the local gravitational potential to identify core boundaries, as described in Gong & Ostriker (2011). There it is shown that the GRID-core method applied to 2D surface density and 3D volume density are in good agreement, for bound cores. This user guide describes how to implement this method on observed surface density. We describe the algorithms used to find the largest closed contour that defines the outer core limit, and to identify the gravitationally bound interior part of the core. In addition, we describe use of the IDL code to implement GRID core-finding on FITS maps. Please cite the original paper (Gong & Ostriker 2011) if you use the code for presentation or publication.

2. Gravitational potential of surface density

For a layer of half-thickness H, the gravitational potential component $\Phi_{\boldsymbol{k},\,2\mathrm{D}}$ of surface density component $\Sigma_{\boldsymbol{k}}$ in phase space is

$$\Phi_{\boldsymbol{k},\,2\mathrm{D}} = -\frac{2\pi G \Sigma_{\boldsymbol{k}}}{|\boldsymbol{k}|\,(1+|\boldsymbol{k}H|)}, \tag{1}$$

where $|\boldsymbol{k}| = \sqrt{k_x^2 + k_y^2}$. Note that for $|\boldsymbol{k}H| \gg 1$, $\Phi_{\boldsymbol{k},\,2\mathrm{D}} \sim -4\pi G \rho_{\boldsymbol{k}}/k^2$, which is the solution of the Poisson equation in three dimensions, for $\rho_{\boldsymbol{k}} = \Sigma_{\boldsymbol{k}}/2H$. For $|\boldsymbol{k}H| \ll 1$, eq. (1) is the solution of the Poisson equation for an infinitesimally thin layer. The gravitational potential $\Phi_{2\mathrm{D}}(x, y)$ is the inverse FT of $\Phi_{\boldsymbol{k},\,2\mathrm{D}}$. In the code, the default value of H is set as δx, the pixel size.

3. The largest closed contour

To identify cores via the gravitational potential, we first find and mark all the local minima of the gravitational potential; second, we find the largest closed potential contour surrounding each individual minimum. In the second step, we increase the contour level from the bottom of a given potential well step by step until it violates another minimum's marked territory by enclosing more than one extremum of the potential. We demonstrate this procedure in Figure 1 using a one

dimensional positive potential, $-\Phi$. In the first step, local maxima (minima in Φ) are marked in a descending order; note that only pixels at extrema are marked in this step. For the second step, we take the local maximum "1" as an example. Starting at $|\Phi_{min}|$, we decrease the isopotential contour level by amount of $\Delta\Phi$ from the top of "1", and find the region which is connected to "1" for each contour level. The blue lines in Figure 1 show the contour levels, and the dotted blue lines show the identified connected regions to the maximum "1". At the 7th contour level, the connected region violates the territories of other maxima, because more than one extremum is contained within the contour (i.e. lying above the lowest blue line, in Fig. 1.). The largest closed contour of "1" is thus defined by the 6th contour level, marked by the red lines. We repeat this procedure on all the local maxima and mark the largest closed contour of each maximum.

The contour interval $\Delta\Phi$ has a negligible effect on the results as long as it is small enough. We define the region enclosed by the largest closed contour as a GRID-core. If the distance between two potential minima is smaller than a certain value of pixels (corresponding to a physical distance which is set by the resolution), the regions associated with these two minima are merged and treated as a single GRID-core.
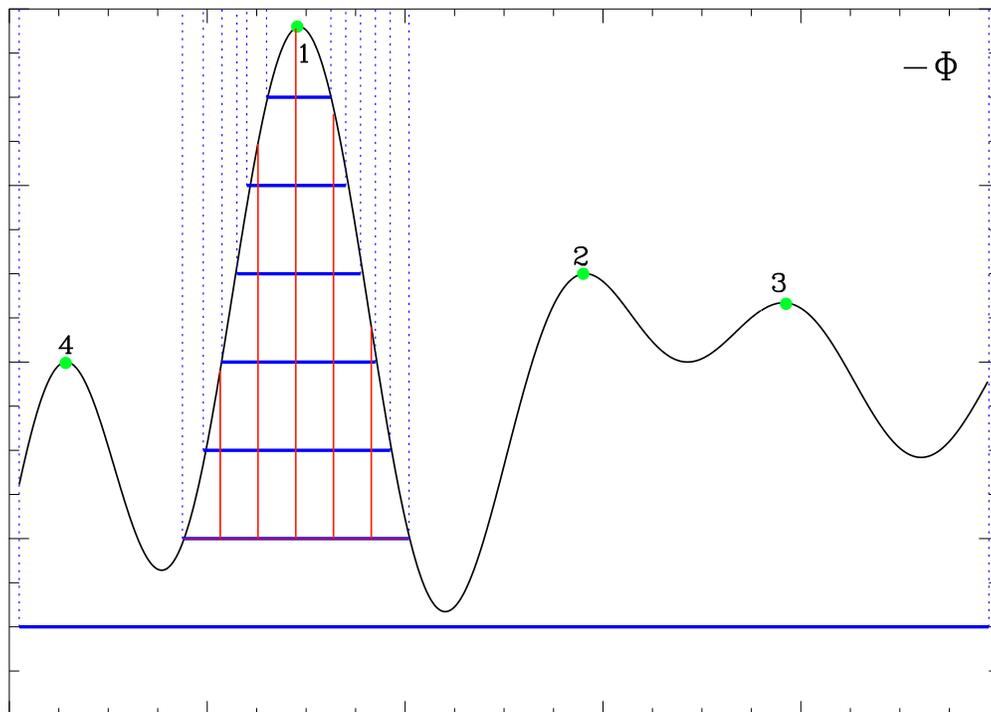
Fig. 1.— Schematic of GRID-core identification method.

4.   Bound thermal cores

Gas with sufficient thermal (and kinetic) energy will not be permanently (or even temporarily) bound to a given core, so the gravitational potential is not the final word. The lower density outer parts of a core are the least bound, and most subject to mass loss.

In order to identify only the bound regions of cores as marked by the gravitational potential, we add thermal energy to the gravitational energy, and only assigning a given fluid element to a core if $E_{\text{th}} + E_g < 0$. For any fluid element, the specific thermal energy is taken to be $E_{\text{th}} = (3/2)c_s^2$, for c_s the isothermal sound speed, and the specific gravitational potential energy is taken to be $E_g = \Phi - \Phi_{\text{max}}$, where Φ_{max} is the potential of the largest closed contour that defines the core. In the example of section 2, Φ_{max} would be equal to the potential of the sixth contour, i.e. $-\Phi_{\text{max}} = -\Phi_{\text{min}} - 6\Delta\Phi$. Including a thermal energy condition decreases the area so that (instantaneously) bound cores are smaller than cores defined by the potential alone. The resulting region is defined as a bound GRID-core.

Of course, the thermal energy can in fact be radiated away, so that gas that is initially near the largest closed contour may become more strongly bound after the interior of a core collapses. Thus, the gas within the outer (unbound) GRID-core region could evolve to become a bound core eventually.

Since bound cores must have $\Phi_{\text{max}} - \Phi_{\text{min}} < (3/2)c_s^2$, a value $\Delta\Phi \sim 0.1c_s^2$ is typically suitable for the potential contour spacing in identifying core boundaries. This is the default value adopted in the code.

We define a background surface density as the mean of the bottom 10% of the surface density; this mean value can be subtracted from the surface density in the core region when calculating core masses.

5.   Structure of the code

The code contains two subroutines: destroy_bad, boundcore2d. The subroutine "destroy_bad" eliminates unresolved cores (total pixel number smaller than $\pi \times$ r_pix_lim^2). The subroutine "boundcore2d" calculates core properties such as the coordinates of core center, total mass of the region inside the largest closed contour, mass of the bound core region, the depth of the gravitational potential well ($\Phi_{\text{max}} - \Phi_{\text{min}}$), and the total number of pixel numbers in marked cores, and bound regions. All the other procedures such as calculating the gravitational potential, and core-finding are handled in the main function. This section explains the function each block in the main function.

The first block is to calculate the gravitational potential of surface density. The surface density in g cm^{-2} is obtained by multiplying input H column density by $1.42m_p$. To create a periodic input for the FFT function, we zero-pad the surface density map in a domain four times as large, putting

the surface density in the lower left quarter and zeros in the other three quarters. The next step is to apply a forward FFT to the extended surface density map. After multiplying by the coefficients as in equation (1), we apply a backward FFT to get the gravitational potential of the extended surface map. At the end of this block, the bottom left part of the gravitational potential field is extracted for later core-finding. Notice that the potential field is converted to positive values.

The second block is to merge local maxima (originally these are minima, since we use $-\Phi$ instead Φ) if they are too close to each other ($r_{\text{distance}} \leq$ cls_dis).

The third block is to do GRID core-finding. The algorithm is described in Section 3. The block to eliminate unresolved cores is right after this block.

6. The IDL program

The calling sequence is:
output=grid_core($filename, pix\_size, T$,cls_dist=cls_dist,dp=dp,h=h,r_pix_lim=r_pix_lim)

ARGUMENTS:
filename : the name of the FITS file containing column density, where the maps is assumed to represent N_H of H nuclei (not H_2), in units of cm^{-2}
pix_size : the pixel resolution of the input column density map, in units of pc

KEYWORDS:

T : temperature of the cloud, using isothermal assumption, in units of K; the default value is 10 K.

dp : the interval between potential contour levels, in units of $c_s^2 = kT/\mu$; the default value is 0.1.

cls_dist : the closest distance between two local potential minima, in units of pix_size; the default value is 6.

h : the minimum thickness of the 2D layer, in units of pix_size; the default value is 1.

r_pix_lim : the minimum radius for a core to be considered resolved, in units of pix_size; the default value is 3, half of cls_dist

OUTPUTS:
1. Two FITS files containing the marked regions identifying cores, e.g.: lcc_0.100.fits (GRID-cores), lcc_b_0.100.fits (bound GRID-cores). The suffix gives the value of dp ("0.100" for the default).
2. A FITS file containing a map of the computed gravitational potential phi.fits ($-\Phi$, in units of $[km/s]^2$).

3. A data file containing the properties of each core: location of potential minimum, total mass of marked region, background-subtracted mass of bound region, pixel numbers of both total and bound regions, gravitational potential $|\Phi_{\min}|$ at the core center, gravitational potential depth $\Phi_{\max} - \Phi_{\min}$.

4. A postscript file showing the marked regions identifying cores: core_on_surfd.ps .

Examples of how to run the code:

1. Setting all keywords –

.run grid_core

output=grid_core("column.fits",0.011,10.,cls_dist=6,dp=0.01,h=1.0,r_pix_lim=3)

2. Using default keywords –

.run grid_core

output=grid_core("column.fits",0.011,10.)

The following figures shows the core-finding results for a column density map, using the first setting.
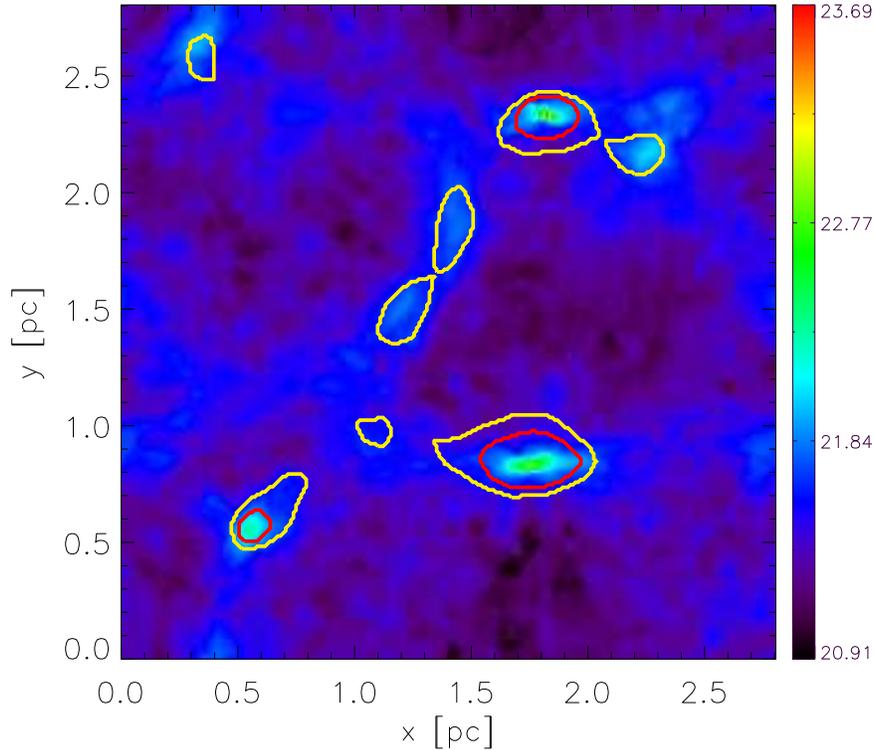
Fig. 2.— GRID core-finding results. The yellow curves are GRID-cores and the red curves are bound GRID-cores. Color scale represents the column density ($\log N_H$).

REFERENCES

Gong, H., & Ostriker, E. C. 2011, arXiv:1101.2650