Contra : A Code for Adiabatic Contraction of Dark Matter Halos
USER GUIDE

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1. About CONTRA

CONTRA is a publicly available code that calculates the contraction of a dark matter halo in response to condensation of baryons in its center. The code is based on the modified contraction model of Gnedin et al. (2004).

The following assumptions are made: The mass distribution of a dark matter halo is spherically symmetric and the velocity distribution is isotropic. The final baryon distribution does not need to be spherical. The code also calculates a line-of-sight velocity dispersion for a tracer population with a given density profile and velocity anisotropy (isotropic, constant β, Osipkov–Merritt, or Mamon–Łokas models).

Input options: There are two ways of specifying the initial dark matter distribution and the final baryon distribution. (i) Analytical distributions commonly used in astronomy: NFW, Exponential, Hernquist, Jaffe, Sersic, or generalized Spherical Sersic models. Tracer population can be one of the above profiles or a power law with a given slope. (ii) Numerical distributions in an optional input file.

Units: $G = 1$, $R_{vir} = 1$, $M_{vir} = 1$ for analytical distributions. For numerical input profiles, the unit of mass is arbitrary but the radii should be in units of the virial radius. All output quantities are in the input units, i.e. the velocity unit is $(GM_{vir}/R_{vir})^{1/2}$.

Download: CONTRA can be downloaded at http://www.astro.lsa.umich.edu/~ognedin/contra/

Install: To install, untar the distribution and type `make`. This should create an executable `contra`.

If you use this code for a publication, please acknowledge the original paper of the modified model:

O. Y. Gnedin, A. V. Kravtsov, A. A. Klypin & D. Nagai, 2004, ApJ, 616, 16 (*"Response of dark matter halos to condensation of baryons: cosmological simulations and improved adiabatic contraction model"*).

2. Command line arguments

CONTRA takes the following command-line arguments:

```
contra MAC DM BAR TRACE ANIS c n_dm
fb rb n_b ra [in_file]
```

2.1. Model of adiabatic contraction MAC

Parameter `MAC` accepts values -1, 0, 1. It describes the model of halo contraction.

`MAC = 0` is the standard model of adiabatic contraction, presented for example in Blumenthal et al. (1986). It is based on conservation of the quantity

$$rM(r) = \text{const}, \tag{1}$$

where $M(r)$ is the total mass of the dark matter and baryons enclosed within radius r.

`MAC = 1` is the modified model adiabatic contraction proposed by (Gnedin et al. 2004). This model reproduces the galaxy and cluster halo profiles in gasdynamics cosmological simulations within 10%. It is based on conservation of the quantity

$$rM(\bar{r}) = \text{const}, \tag{2}$$

where r is the instantaneous radius of an ensemble of particles, and $\bar{r}$ is the orbit-averaged radius. Currently, the orbit-averaged radius is implemented using the parametrization of Gnedin et al. (2004):

$$\bar{r}/R_{vir} = A\,(r/R_{vir})^{w}, \tag{3}$$

with fiducial values $A = 0.85$ and $w = 0.8$ corresponding to typical distributions of particles in CDM halos. The values of A and w can be modified by the user.

`MAC = −1` does not calculate halo contraction and copies the input DM profile to the output profile. This option allows the user to calculate the line-of-sight velocity dispersion for a given input profile.

2.2. Initial dark matter profile `DM`

Parameter `DM` accepts values 1, 2, 3. It describes the initial density profile of both dark matter and baryons.

`DM` = 1 is an NFW profile (Navarro et al. 1997), `DM` = 2 is a generalized spherical Sersic model, described in Navarro et al. (2004), `DM` = 3 is a model for tidally-truncated satellite halos, described in Kazantzidis et al. (2004). Functionally, the dark matter mass fraction is defined as

$$m_h(x) = (1 - f_b) \frac{M_h(x)}{M_h(1)}, \qquad (4)$$

where $x \equiv r/R_{\rm vir}$, $c \equiv R_{\rm vir}/r_s$, and

$$\text{DM} = 1: \qquad M_h(x) = \ln(1 + cx) - \frac{cx}{1 + cx} \qquad (5a)$$

$$\text{DM} = 2: \qquad M_h(x) = \gamma\left(3n, 2n(cx)^{1/n}\right) \qquad (5b)$$

$$\text{DM} = 3: \qquad M_h(x) = \gamma(3 - \nu, cx) \qquad (5c)$$

where $n \equiv n_{\rm dm}$, and $\gamma(a, x) \equiv \int_0^x t^{a-1} e^{-t} dt$ is the incomplete gamma function. The latter profile corresponds to the density distribution $\rho(r) \propto r^{-\nu} \exp(-r/r_s)$, which describes the profile of tidally-truncated satellite halos in high-resolution simulations of Kazantzidis et al. (2004).

2.3. Final baryon profile `BAR`

Parameter `BAR` accepts values 1, 2, 3, 4. It describes the final density profile of condensed baryons. It typically applies to stars and cold gas (with combined mass fraction f_b), while any hot gas present in the system may be assumed to have a similar final profile to dark matter (with combined mass fraction $1 - f_b$).

`BAR` = 1 is an exponential disk, `BAR` = 2 is a Hernquist (1990) model, `BAR` = 3 is a Jaffe (1983) model, `BAR` = 4 is the original Sersic (1968) model, many properties of which are worked out in Prugniel & Simien (1997). The baryon mass fraction is

$$m_b(x) = f_b \frac{M_b(x)}{M_b(1)} \qquad (6)$$

$$\text{BAR} = 1: \qquad M_b(x) = 1 - (1 + x/r_b)e^{-x/r_b} \qquad (7a)$$

$$\text{BAR} = 2: \qquad M_b(x) = \frac{x^2(1 + r_b)^2}{(x + r_b)^2} \qquad (7b)$$

$$\text{BAR} = 3: \qquad M_b(x) = \frac{x(1 + r_b)}{(x + r_b)} \qquad (7c)$$

$$\text{BAR} = 4: \qquad M_b(x) = \gamma\left((3 - p)n, (x/r_b)^{1/n}\right), \qquad (7d)$$

where $n \equiv n_{\rm b}$, and $p \equiv 1 - 0.6097/n + 0.05563/n^2$ in the Sersic profile is from Lima Neto et al. (1999); Márquez et al. (2000).

2.4. Tracer population `TRACE`

Parameter `TRACE` accepts values 1, 2, 3, 4, 5, 6, 7. It describes the density profile of the tracer population, for which CONTRA calculates the velocity dispersion. The normalization of the tracer density is arbitrary.

`TRACE` = 1 is an exponential disk, `TRACE` = 2 is a Hernquist model, `TRACE` = 3 is a Jaffe model, `TRACE` = 4 is a Plummer (1911) model, `TRACE` = 5 is an NFW model, `TRACE` = 6 is the original Sersic model, `TRACE` = 7 is the spherical Sersic model, and `TRACE` < 0 gives the slope of a power law density profile. The density distribution of the tracer population is used to calculate the line-of-sight velocity dispersion.

$$\text{TRACE} = 1: \qquad \rho_{\rm tr}(x) \propto e^{-x/r_b} \qquad (8a)$$

$$\text{TRACE} = 2: \qquad \rho_{\rm tr}(x) \propto \frac{1}{x(x + r_b)^3} \qquad (8b)$$

$$\text{TRACE} = 3: \qquad \rho_{\rm tr}(x) \propto \frac{1}{x^2(x + r_b)^2} \qquad (8c)$$

$$\text{TRACE} = 4: \qquad \rho_{\rm tr}(x) \propto \frac{1}{(x^2 + r_b^2)^{5/2}} \qquad (8d)$$

$$\text{TRACE} = 5: \qquad \rho_{\rm tr}(x) \propto \frac{1}{x(x + r_b)^2} \qquad (8e)$$

$$\text{TRACE} = 6: \qquad \rho_{\rm tr}(x) \propto x^{-p} \exp\left[-(x/r_b)^{1/n}\right] \qquad (8f)$$

$$\text{TRACE} = 7: \qquad \rho_{\rm tr}(x) \propto \exp\left[-2n(x/r_b)^{1/n}\right] \qquad (8g)$$

2.5. Type of anisotropy distribution `ANIS`

Parameter `ANIS` accepts values 0, 1, 2, 3. It describes anisotropy of the velocity distribution of the tracer population.

`ANIS` = 0 is an isotropic velocity distribution, `ANIS` = 1 is a constant anisotropy parameter

$$\text{ANIS} = 1: \qquad \beta = \text{const}, \qquad (9)$$

`ANIS` = 2 is the Mamon & Łokas (2005) anisotropy profile:

$$\text{ANIS} = 2: \qquad \beta(r) = \frac{1}{2} \frac{r}{r + r_a}, \qquad (10)$$

where r_a is the anisotropy radius (specified below), `ANIS` = 3 is the Osipkov-Merritt anisotropy profile:

$$\text{ANIS} = 3: \qquad \beta(r) = \frac{r^2}{r^2 + r_a^2}. \qquad (11)$$

2.6. Other input parameters

`c` is the initial halo concentration parameter, $c = R_{\rm vir}/r_s$, used in eq. (5).

$n_{\rm dm}$ is the index of a spherical Sersic profile for dark matter, used in eq. (5b), and for the tracer population, used in eq. (8g).

fb is the baryon fraction within the virial radius, $f_b = M_b/M_{\rm vir}$.

rb is the baryon scalelength in units of the virial radius, $r_b/R_{\rm vir}$, used in eq. (7), as well as the tracer population scalelength, used in eq. (8).

$n_{\rm b}$ is the index of the original Sersic profile for baryons, used in eq. (7d), and for the tracer population, used in eq. (8f). It can also be used to set the upper limit of integration for the velocity dispersion (see §3 below).

ra is the radius of velocity anisotropy for tracer population, $r_a/R_{\rm vir}$, used in eqs. (10) and (11), or the β parameter in case ANIS = 1.

2.7. Numerical profile

A different input option is to read a numerical profile from an ASCII file. The last (optional) command line argument in_file specifies the name of the file. All previous numerical parameters are then ignored.

The input format for in_file contains six input columns: grid of the initial radii r_i, initial baryon enclosed mass $m_{{\rm b}i}$, initial dark matter enclosed mass $m_{{\rm h}i}$, grid of the final radii for the baryon profile $r_{{\rm b}f}$, final baryon enclosed mass $m_{{\rm b}f}$, density of the tracer population on the *initial* radial grid $\rho_{\rm tr}$.

3. Velocity dispersion

The calculation of the line-of-sight velocity dispersion in the combined potential of baryons and dark matter is based on the analysis in Mamon & Łokas (2005, 2006):

$$\sigma_{\rm los}^2(R) = \frac{2G}{I(R)} \int_R^{R_{\rm max}} K\left(\frac{r}{R}, \frac{r_a}{R}\right) \rho_{\rm tr}(r) \frac{M(r)}{r} dr, \quad (12)$$

where $M(r)$ is the total mass enclosed within radius r, $I(R)$ is the surface density of the tracer population at the projected radius R:

$$I(R) = 2 \int_R^{R_{\rm max}} \rho_{\rm tr}(r) \frac{r}{\sqrt{r^2 - R^2}} dr. \quad (13)$$

The dimensionless kernel $K(r/R, r_a/R)$ is given by eq. (A16) of Mamon & Łokas (2005).

Based on the result of Prada et al. (2006) that galaxy-sized dark matter halos in cosmological simulations typically extend well beyond the nominal virial radius, we take the upper limit of integration to be $R_{\rm max} = 3R_{\rm vir}$. $R_{\rm max}$ can be thought of as the truncation radius of the tracer population. A different value

of $R_{\rm max}/R_{\rm vir}$ can be passed via the input parameter $n_{\rm b}$, if TRACE < 6 and BAR < 4.

The calculation of the line-of-sight velocity dispersion is the most computationally intensive part of CONTRA. If the dispersion is not needed, set TRACE = 0 to avoid its computation.

4. Output

The standard output is mapped to the grid of initial radii r_i, by interpolation where necessary. For analytical input profiles, the initial grid is created automatically and ranges from $10^{-4}R_{\rm vir}$ to $R_{\rm vir}$.

The output columns are: initial grid of radii (r_i), contracted radii (r_f), initial dark matter mass enclosed within r_i (m_i), final enclosed dark matter mass enclosed (m_f), initial dark matter density (ρ_i), final dark matter density at r_i (ρ_f), initial logarithmic slope of dark matter density (γ_i), final logarithmic slope of dark matter density (γ_f), final circular velocity of dark matter plus baryons (v_c), line-of-sight velocity dispersion of the tracer population at the projected radius $R = r_i$ ($\sigma_{\rm los}$).

Note that a very strong baryon concentration at the center may lead to a formal "shell crossing" for the assumed spherical dark matter distribution. In this case even the modified adiabatic contraction model is not valid and may result in the unphysical negative density. The output of CONTRA should be ignored where unphysical density occurs.

5. Examples

Examples will be added later.

6. Feedback

CONTRA can be extended to include additional features. Please direct all comments and suggestions to ognedin@umich.edu.

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