A Tejútrendszer dióhéjban

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Outline

The Milky Way galaxy

What is the Milky Way?

A complex system of gravitationally bound stars, interstellar gas and dust and perhaps dark matter

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- There are some interesting nomenclatures in our region, too:
  - The Path of Armies (Star-path of Prince Csaba)
  - The Path of the Fallen Souls
  - The Dewy Way (The Path of the Fairies)
  - The Fairy Silk Tissue
  - The Straw Way (The Way of the Gypsy, St. Peter's Way)

A little bit of history

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- **From the 1920s** - observations of other galaxies

Our current knowledge - A fact sheet

The recipe of understanding our Galaxy

Observations of other galaxies + Statistical methods + Precise observational campaigns

Type	Sbc-type barred spiral	Gerhard (2002)
$R_{visible}$	~ 31 kpc	Lopez-Corredoira et al. (2018)
R_{DM}	~ 292 kpc	Deason et al. (2020)
$R_{\odot}$	~ 8.122 kpc	Gravity Collaboration et al. (2018)
Count of stars	$200 - 400$ billion	*many estimates*
$M_{overall}$	1.18×10^{12} $M_{\odot}$	Watkins et al. (2019)

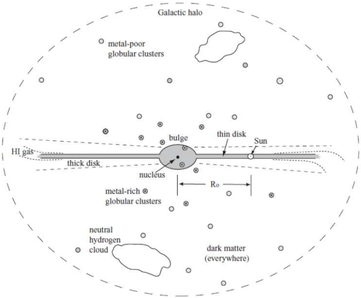
The morphology of the Galaxy

Mapping and creating a model of a complex system of stars and interstellar material from the inside of such system is a challenging task.

It can be done via

- Observing galexies beyond the MW
- Creating abundance analyses
- Measuring parallaxes

THE CURRENT MODEL - IN PICTURES



(a)

(b)

FIGURE: (a): Schema of the Milky Way. *Credit:* Sparke and Gallagher III (2007). (b): Galaxy NGC 3953. *Credit:* Wilson (2010).

The current model - Structures of the MW

- Thick & thin disks

Properties

•Not completely cylindrically symmetric, rather elliptic
•Thin disk - younger stars & interstellar medium
•$z_{\text{thin}} \sim 350\ (90)$ pc
•$M_{\text{thin}} \sim 6\ (0.5) \times 10^{10}$ $M_\odot$
•Thick disk - older stars
•$z_{\text{thick}} \sim 1000$ pc
•$M_{\text{thin}} \sim 3 \times 10^{10}$ $M_\odot$

The current model - Structures of the MW

- Thick & thin disks

Properties

•Thin disk is composed of the metal-rich and young Population I stars with $[Fe/H] \sim 0.02$
•Thick disk contains metal-poor and older stars with $[Fe/H] \sim 0.001$
•Peculiar metallicity Population III discovered (Carollo et al., 2019)

The current model - Structures of the MW

- Thick & thin disks

Properties

•Spiral arms formed by O and B stars, H II region and stellar open clusters
•Quasi-stationary density wave in which a particular wave pattern stays in place, though the material forming the spiral does not reside in the location of the spiral
•The spiral arms have a major role in star formation

The current model - Structures of the MW

- Thick & thin disks
- Interstellar gas & dust

Properties

•most of ISM is located near the Galactic midplane, especially the molecular H_2 and dust
•Mass of HI: 4×10^9 $M_\odot$
Mass of H2: 10^9 $M_\odot$
•Gas density in the Solar neighbourhood is: 0.04 $M_\odot pc^{-3}$
•Its main components are hydrogen (77%), molecules (17%) and ions (6%).

The current model - Structures of the MW

- Thick & thin disks
- Interstellar gas & dust
- Warp & flare

Properties

•Almost every disk galaxy has a noticeable warp (infra HI observations)
•Close approaches of galaxies or a collision with a dwarf galaxy could create a mechanical wave, which causes the warp of the Galactic disk
•Flare - increment of galactic disk scale height with the galactocentric distance

The current model - Structures of the MW

- Thick & thin disks
- Interstellar gas & dust
- Warp & flare
- Bulge & bar

Properties

•In the central region of the Galactic disk the vertical scale height increases and creates the bulge.
•$M_{bulge} = 10^{10}\ M_{\odot}$
•It contains stars of various metallicities
•Bar is a substructure of the bulge
•Its shape is caused by the interaction of the inflowing gas from the spiral arms and the radiation waves from the Galactic Center, which leads to changes in the orbits of stars in the bulge

The current model - Structures of the MW

- Thick & thin disks
- Interstellar gas & dust
- Warp & flare
- Bulge & bar
- Galactic center

Properties

•Extinction of more than 30 magnitudes in visible wavelengths
•Hot and dense molecular clouds 10^6 M$_\odot$
•Stellar nucleus (0.2 pc) 3×10^7 M$_\odot$ pc^{-3}
•Saggitarius A* - 3.7×10^6 M$_\odot$, 16 R$_\odot$

The current model - Structures of the MW

- Thick & thin disks
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- Bulge & bar
- Galactic center
- Stellar halo

Properties

•Contains globular clusters and field stars
•Both are old metal-poor objects
•Currently 150 known globular clusters with distances from 500 pc to 120 kpc from the GC (11 - 13 Gyr)
•Stellar streams - remnants of tidally shredded dwarf galaxies.

The current model - Structures of the MW

- Thick & thin disks
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- Stellar halo
- Dark matter halo

Properties

•Based on its gravitational influence over baryonic matter, there should be:
•5.4×10^{11} $M_\odot$ of DM within 50 kpc from the GC
•1.9×10^{12} $M_\odot$ of DM within 230 kpc from the GC
•Which makes up about 95 % of the Galaxy

The current model - Structures of the MW

- Thick & thin disks
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- Bulge & bar
- Galactic center
- Stellar halo
- Dark matter halo
- Satellite galaxies

Properties

•About 60 known dwarf galaxies within 420 kpc radius
•Most of them are old spheroidal ones
•There are numerous traces of collisional and merger events with the Milky Way (the warp, stellar populations, new structures ...)

Defining the coordinate systems

An appropriate system of coordinates

Takes advantage of the natural symmetry of the Galactic disk

Three coordinate systems are commonly used:

- Galactic coordinate system (l, b)
- Cylindrical coordinate system (R, θ, z)
- Cartesian coordinate system (x, y, z)

THE GALACTIC COORDINATE SYSTEM

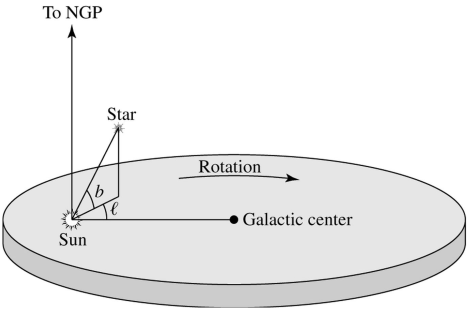
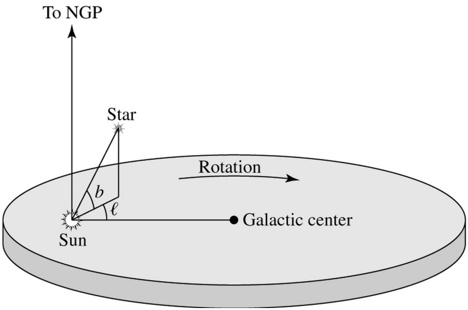


FIGURE: *Credit:* Carroll & Ostlie (2006)

The Galactic coordinate system



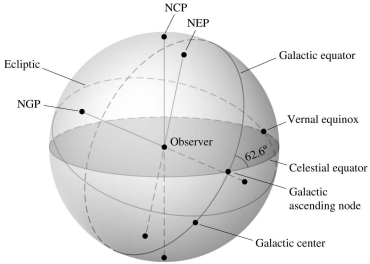
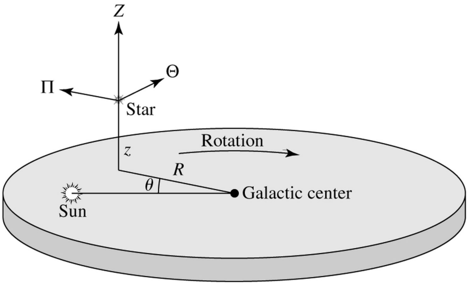


Figure: *Credit:* Carroll & Ostlie (2006)

The cylindrical coordinate system



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Velocity components

$$\Pi = \dot{R}, \quad \Theta = R\dot{\theta}, \quad Z = \dot{z}$$

The LSR and the (peculiar) motions

The Local Standard of Rest

Is a point that is always centered on the Sun and moves on a perfectly circular orbit around the Galactic center
(Or, the average motions of stars around the solar neighbourhood.)

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$$\Theta_{LSR} = \Theta_0(R_0) = (230 \pm 3)\ \text{km s}^{-1} \qquad \text{(Vallée, 2017)}$$

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$$\Theta_{LSR} = \Theta_0(R_0) = (230 \pm 3)\ \text{km s}^{-1} \qquad \text{(Vallée, 2017)}$$

- However, this values widely varies between authors

$$\Theta_{LSR} = 220 - 240\ \text{km s}^{-1}$$

The LSR and the (peculiar) motions

The peculiar motions

The relative velocity of a star to the LSR is called *peculiar velocity*

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The peculiar motions

The relative velocity of a star to the LSR is called *peculiar velocity*

- If we measure a star's velocity, in fact we measure the difference between the star's and Sun's peculiar velocity
- Overall peculiar velocity of the Sun (Solar motion) is

$$13.4 \text{ km s}^{-1}$$

towards the constellation Hercules

The motion of stars

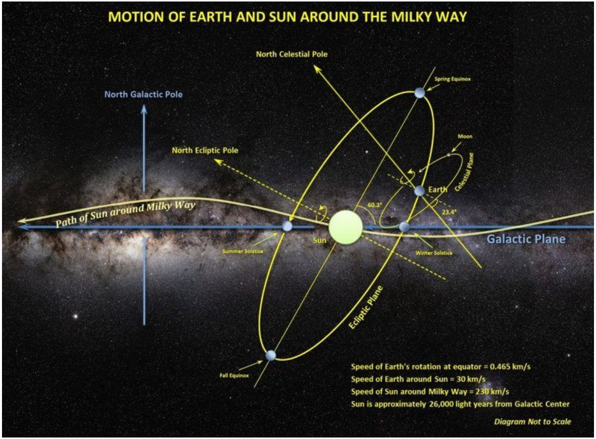

Figure: *Credit:* This blog

The motion of stars

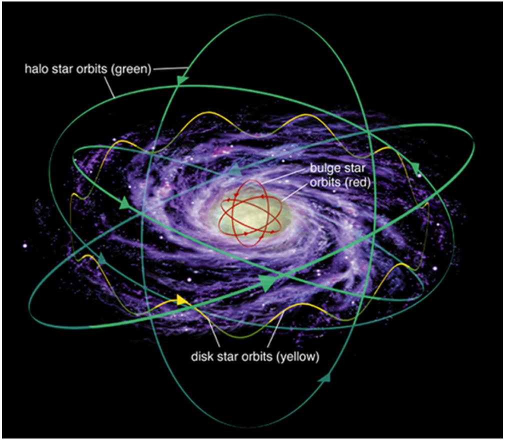

Figure: *Credit:* This lecture

Differential rotation

Why?

The Galactic disk(s) does not rotate as a solid wheel, the orbital period varies with the Galactocentric distance

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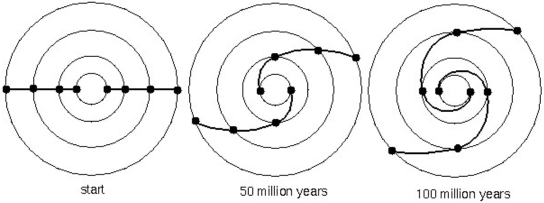

Figure: Differential rotation. *Credit:* This lecture

Differential rotation

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The Oort's constants

This rotation could be described by the Oort's constants

$$A = (15.3 \pm 0.4)\ \mathsf{km\ s}^{-1}\ \mathsf{kpc}^{-1}\ ,$$

$$B = (-11.9 \pm 0.4)\ \mathsf{km\ s}^{-1}\ \mathsf{kpc}^{-1}\ .$$

where A describes the shearing motion, while B describes the vorticity, the Galactic rotation in the solar neighbourhood

Galactic dynamics in a very nutshell

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If galaxies obey Newton's law of universal gravitation

... there must be an excess of unseen mass

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Up till now

Dark matter remains unexplained

Galactic dynamics in a very nutshell

What if Newton was wrong?

There would be no need for the dark matter. Maybe the gravity works in a different way ...

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- **1983 - today** - Many unsuccessful MOND & MOG (Modified gravitation) theories
- **Klačka (2019)** - Proposal of the Generalized (and modified) gravitation based on the latest observations

Introduction to Galactic dynamics

- Replacing Newton's law with the Poisson's equation one can describe the relation between the gravitational force and mass as

$$\vec{\nabla}^2\phi(\vec{r}) = 4\pi G\rho(r)$$

- it is assumed that the Poisson's equation holds on the scale of galaxies and the Universe

In order to study dynamics of galaxies

the mass density distribution $\rho(r)$ and the gravitational potential $\phi(r)$ must be determined

Why are density and potential such crucial?

- A discrete and collisionless system of N point masses could be defined by a six-dimensional phase-space density (distribution function) :

$$f(\vec{r}, \dot{\vec{r}}, t)\ \mathrm{d}^3\vec{r}\ \mathrm{d}^3\dot{\vec{r}}$$

- Collisionless system - time derivative must be zero as the flow in the phase-space is incomprehensible:

$$\dot{f}(\vec{r}, \dot{\vec{r}}, t) = 0$$

The Vlasov equation

completely specifies the evolution of a collisionless system

Why are density and potential such crucial?

- Once the distribution function is obtained, the density could be obtained straightforward by integrating over the velocity space:

$$\rho(\vec{r},t) = \iiint f(\vec{r},\dot{\vec{r}},t)\ \mathrm{d}^3\dot{\vec{r}}$$

- while the total mass of the system is determined from:

$$M(t) = \iiint f(\vec{r},t)\ \mathrm{d}^3\vec{r} = \int \mathrm{d}^3\vec{r} \int \mathrm{d}^3\dot{\vec{r}}\ f(\vec{r},\dot{\vec{r}},t)$$

The gravitational potential

must be constructed reasonably

Example - Simple spherical potential

To present how to obtain the gravitational force, we will derive Newton's universal gravitation. Considering a simple spherical density distribution $\rho(r)$ we obtain the Poisson's equation as follows:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \phi}{\partial r}\right) = 4\pi G\rho(r) \ ,$$

from which we obtain

$$r^2\frac{\partial \phi}{\partial r} = 4\pi G\int_0^r \rho(r)r^2 \ \mathrm{d}r = GM(r),$$

where $M(r)$ is the total enclosed mass. Recalling that acceleration is the negative gradient of the potential we obtain Newton's gravitational force:

$$\vec{F}(\vec{r}) = -\vec{\nabla}\phi(\vec{r}) = -\frac{\mathrm{d}\phi}{\mathrm{d}r}r = -\frac{GM(r)}{r^2}r \ ,$$

where $\vec{r}$ is position vector with respect to the center of the mass and r is the unit position vector. While the gravitational potential which obeys both Newton's law and the Poisson's equation is

$$\phi(\vec{r}) = -\frac{GM(r)}{r} \ .$$

The Galactic rotation curve

- The circular velocity is determined from the relation

$$v_c(R) = \sqrt{R\frac{\partial}{\partial R}\left(\phi_{\text{Total}}\right)}$$

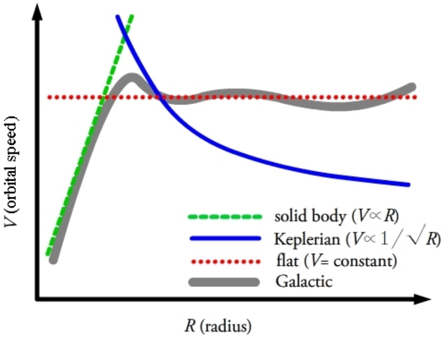

Figure: Rotation curves. *Credit:* This website.

How does a real ϕ_{Total} look like?

$$\phi_{\text{Thick disk}}(R,z) = \frac{-GM_{\text{Thick disk}}}{\left[R^2 + \left(a_{\text{Thick disk}} + \sqrt{z^2 + b^2_{\text{Thick disk}}}\ \right)^2\right]^{1/2}} ,$$

$$\phi_{\text{Thin disk}}(R,z) = \frac{-GM_{\text{Thin disk}}}{\left[R^2 + \left(a_{\text{Thin disk}} + \sqrt{z^2 + b^2_{\text{Thin disk}}}\ \right)^2\right]^{1/2}} ,$$

$$\phi_{\text{Bulge}}(R) = \frac{-GM_{\text{Bulge}}}{\left(R^2 + b^2_{\text{Bulge}}\right)^{1/2}} ,$$

$$\phi_{\text{DM halo}}(R) = \frac{-GM_{\text{DM halo}}}{R} - \frac{M_{\text{DM halo}}}{1.02 a_{\text{DM halo}}} \times \left[\frac{-1.02}{1 + (R/a_{\text{DM halo}})^{1.02}} + \ln\left(1 + \left(\frac{R}{a_{\text{DM halo}}}\right)^{1.02}\right)\right]_R^{100} .$$

How does a real ϕ_{Total} look like?

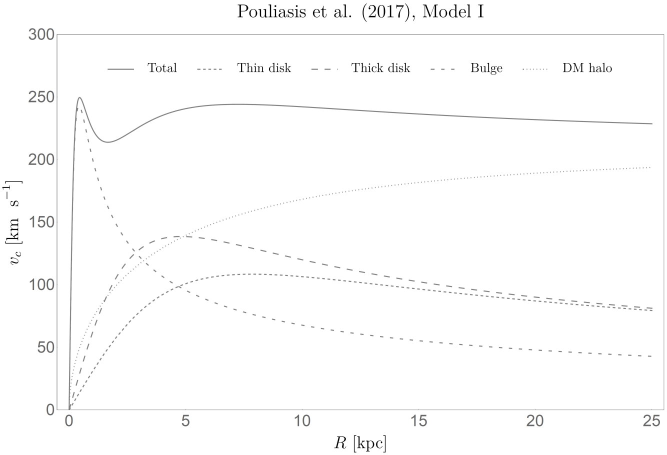

Figure: Rotation curves produced from potential model I of Pouliasis et al. (2017).

MOND and MOG

Modified Newtonian Dynamics

the force due to the Newtonian gravity for very small values of acceleration $|\vec{a}|$ is scaled as

$$m\frac{|\vec{a}|}{a_0}\vec{a} = g_{bar}$$

(Milgrom, 1983)

Modified Gravitation

keeps Newton's second law in it's original form, but changes the gravitational force

$$m\vec{a} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_\dagger}}}$$

(McGaugh et al., 2016), (Klačka, 2019)

$$g_{bar} = -\frac{GMm}{|\vec{r}|^3}\vec{r}\,; \qquad a_0 = g_\dagger = (1.2 \pm 0.02) \times 10^{-10}\ \mathrm{m\ s^{-2}}$$

Observational surveys

Anders et al. (2019)

"Galactic astrophysics is currently in a similar phase as geography was in the 15th century: large parts of the Earth were unknown to contemporary scientists, only crude maps of most of the known parts of the Earth existed, and even the orbit of our planet was still under debate. Nowadays, major parts of the Milky Way are still hidden by thick layers of dust, but we are beginning to discover and to map our Galaxy in a much more accurate fashion by virtue of dedicated large photometric, astrometric, and spectroscopic surveys."

Surveys AG (anno Gaia)

- Hipparcos

Achievements

•The first astrometric telescope in space
•Astrometric and photometric data from 1989 to 1993
•Overall 118 218 stars observed
•Tycho 2 Catalogue (Hog et al., 2000) 2.5 million stars - 99 % of stars down to magnitude 11
•The widest catalogue of stars at the end of the millennium.

Surveys AG (anno Gaia)

- Hipparcos
- 2MASS

Achievements

•Ground-based observational campaign
•Two dedicated telescopes covered 99% of the celestial sphere in near-infrared bandpass
•4.1 million FITS images of the entire night sky and over 461 million objects with astrometry and photometry, including stars, brown dwarfs, minor objects in the Solar System, gas nebulae and stellar clusters (Skrutskie et al., 2006)

Surveys AG (anno Gaia)

- Hipparcos
- 2MASS
- WISE

Achievements

•Successor of 2MASS
•Its goals were to search for the origin of planets, stars and galaxies and to create an infrared map of the Universe
•Its catalogue contains (i) positions, apparent motions and flux variability statistics for more than 747 million objects, (ii) a photometry database containing 42 billion time-tagged measurements and (iii) an image atlas with ~ 18000 FITS images.

Surveys AG (anno Gaia)

- Hipparcos
- 2MASS
- WISE
- SDSS

Achievements

•Its goal is to create a map of the Universe and the distribution of the luminous and non-luminous matter.
•Still operating, from 2000.
•So far imaged 8000 square degrees of the sky, measured spectra of more than 700 000 objects and mapped one million galaxies and 100 000 quasars
•Currently is observing with extended cosmological precision, it creates the first spatially resolved maps of galaxies and its expanding the spectroscopic survey of the Milky Way galaxy.

Surveys AG (anno Gaia)

- Hipparcos
- 2MASS
- WISE
- SDSS

Achievements

•All together the SDSS is **probably the most successful survey** in the history of astronomy.

Surveys AG (anno Gaia)

- Hipparcos
- 2MASS
- WISE
- SDSS
- APOGEE

Achievements

•Is a part of the SDSS survey
•Infrared spectroscopy observations of Galactic disk and bulge
•With 163000 targets, it is the largest scale spectroscopic survey of our Galaxy
•The upcoming Data release will include more than 430000 stars.

The billion star surveyor

Gaia

The Global Astrometric Interferometer for Astrophysics was launched in 2013 as a successor of Hipparcos

- Instruments: two identical optical telescopes, a radial velocity spectrometer, blue and red photometers.
- The payload features a focal plane array (0.5 m x 1 m) with 106 CCD detectors containing nearly 1 billion pixels, making it the largest digital camera ever used in space.
- Was planned for a five-year mission. However, an extension was approved until the end of 2022.

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Definite catalogue of the foreseeable future

Data collected by Gaia throughout its mission will be used to eventually build the most accurate three-dimensional map of the positions, motions, and chemical composition of stars in our Galaxy

Data Release 3

EDR3 (3^{RD} of December 2020)

The full DR3 in will released in the 2^{nd} half of 2021

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EDR3 (3rd of December 2020)

The full DR3 in will released in the 2^{nd} half of 2021

- positions, parallaxes and proper motions for ~ 1.5 bil. stars
- photometry for 1.8 billion sources
- about 1.5 mil. celestial reference frame sources (quasars)
- cross-matches between EDR3 and: DR2, Hipparcos-2, Tycho-2, 2MASS PSC, SDSS DR13, Pan-STARRS1 DR1, SkyMapper DR1, GSC 2.3, APASS DR9, RAVE DR5, allWISE, and URAT-1 data on the other hand

The ultimate Gaia catalogue

Gaia catalogue (end of the 2020's)

The release date is still unknown as additional mission extensions may occur

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- all available variable, binary and multiple stars solutions
- additional astrophysical parameters for stars, unresolved binaries, galaxies and quasars
- exoplanet catalogue
- all epoch and transit data for all sources

Thank you for your attention

"But high above there is the cloudless sky of purity and light and grandeur too, as frail yet firm as everything that's true."

- Dezső Kosztolányi, *Dawnstruck*