Group Meeting

Minor planets, asteroids, comets and interplanetary dust within 30 au

Quanzhi Ye

Reporter: Yuhao Liu

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YUNNAN UNIVERSITY 1923

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Outline

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Ⅰ. Introduction

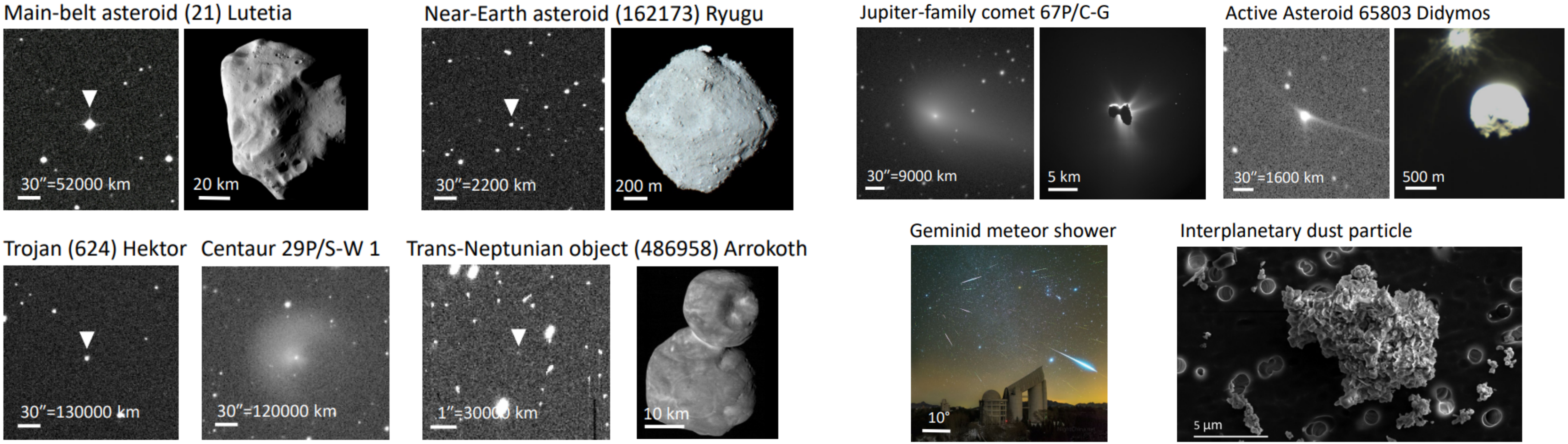
Our Solar System contains much more than just the Sun, the Moon, and the planets. In fact, small Solar System bodies – loosely defined as minor planets, asteroids, comets, and interplanetary dust – are the most numerous objects in the Solar System.

As of mid-2024, approximately 1.4 million minor planets (including asteroids) and 5,000 comets have been cataloged.

Studying them provides valuable insights into planetary formation and evolution, the potential threats posed by near-Earth asteroids and comets, and the origins of life and life-essential materials such as water.

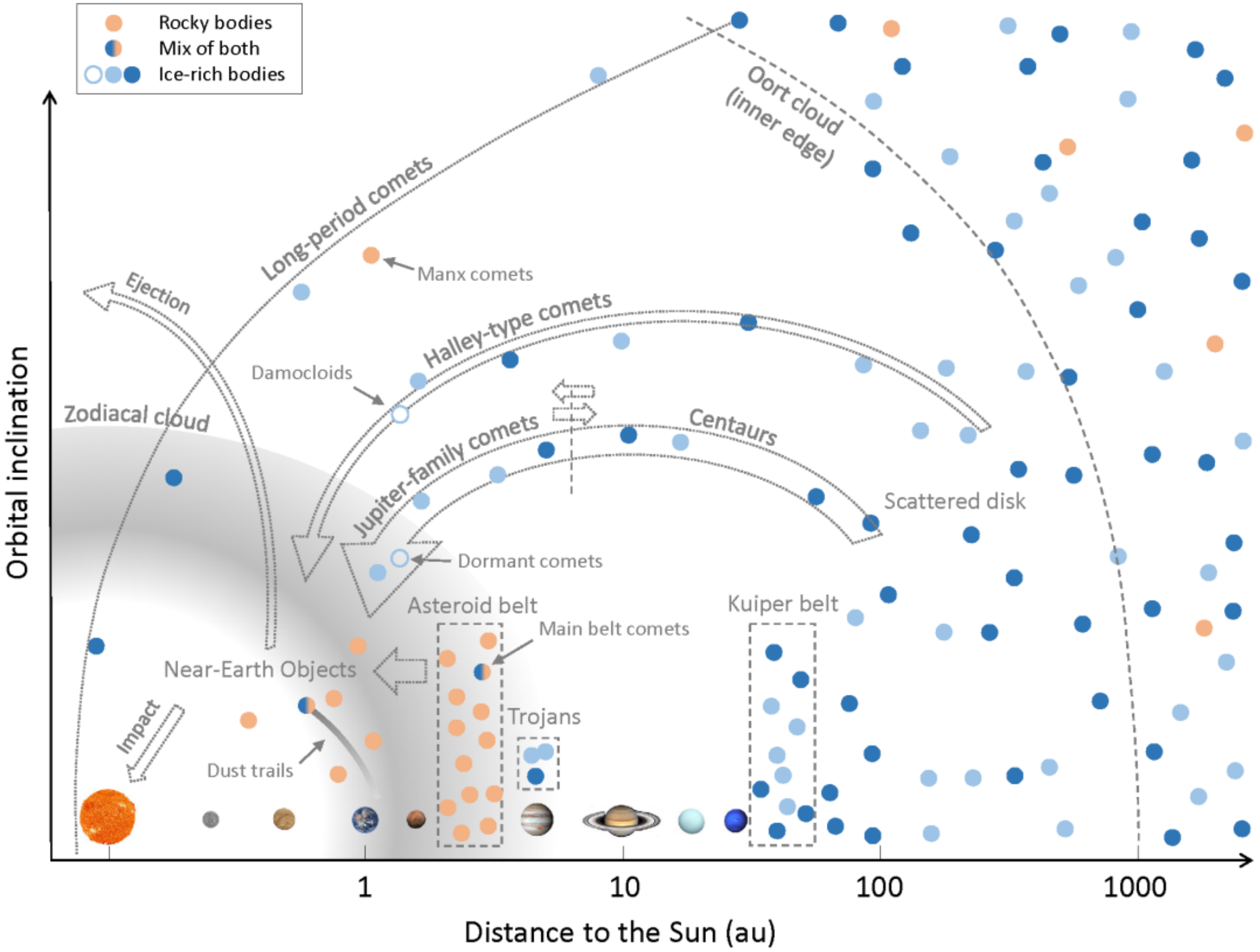
Ⅰ. Introduction

Different types of small bodies:



Ⅰ. Introduction

Key small body populations and their interrelations:



Minor Planets

the term "minor planet" generally encompasses asteroids within Jupiter's orbit as well as nearly all objects beyond, except for comets.

Small Bodies

The 2006 IAU resolution defined a small body as an object in the Solar System that is neither a planet, dwarf planet, nor a moon, effectively including most minor planets and comets.

Asteroids

The term asteroids originally referred to bodies found in the asteroid belt but has since been expanded to include any non-cometary bodies that orbit the Sun, particularly those within the orbit of Jupiter.

Comets

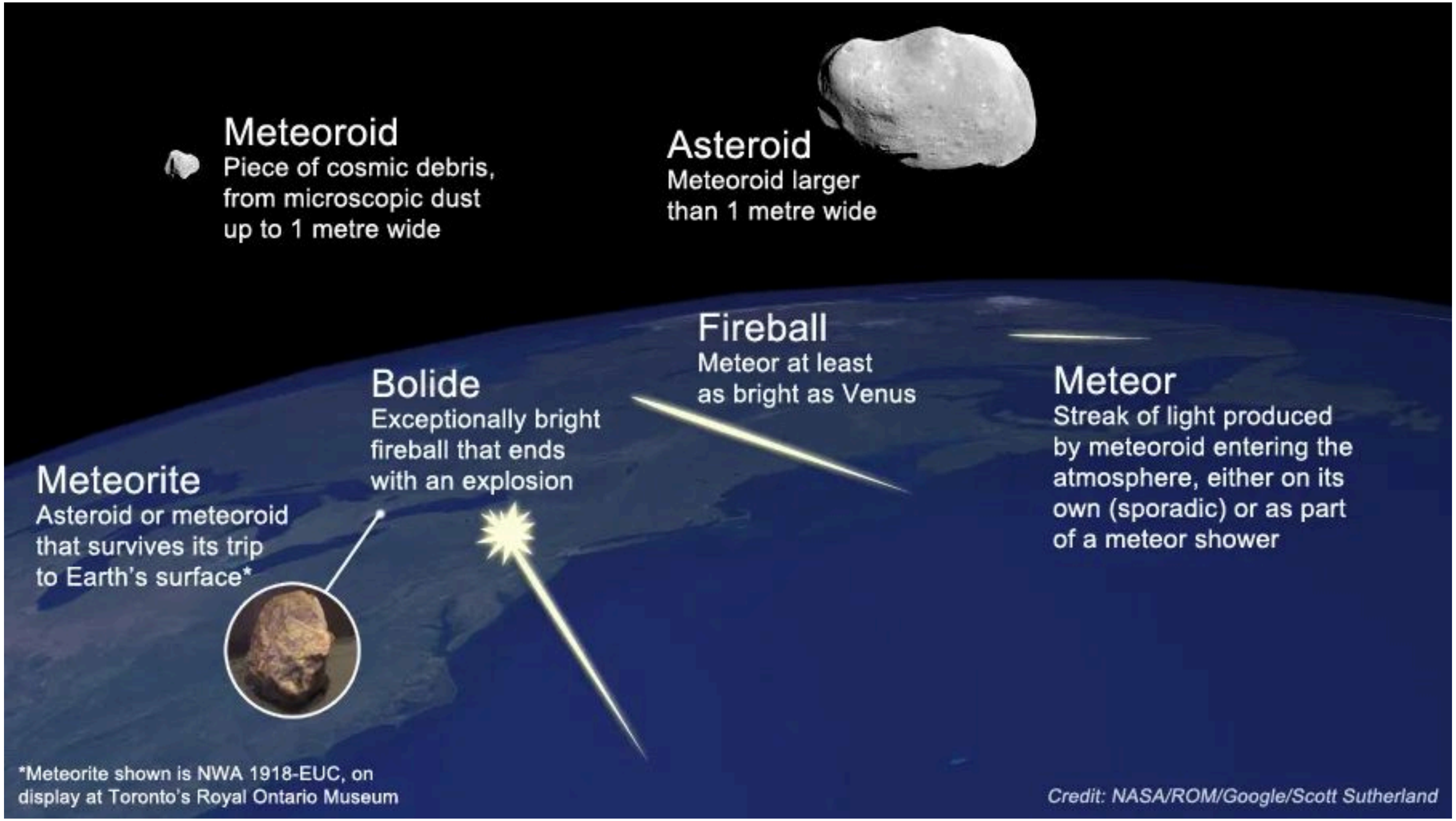
A comet is an object that exhibit a coma (an extended atmosphere surrounding the nucleus) and/or tail(s).

Objects smaller than ~ **1 m** encompass various dust and meteor-related populations, such as:

Interplanetary Dust
This term refers to all dust particles within the Solar System. While it is sometimes used interchangeably with *interplanetary dust particles* (**IDPs**).

Meteoroids
Meteoroids are larger interplanetary dust with sizes ranging from ~ 30 μm to about a meter. When meteoroids collide with planets or moons, they can produce **meteors** and impact flashes. Meteors with apparent magnitudes of < -4 and < -14 are called **fireballs** and **bolides**, respectively. Meteoroids at the small end are sometimes called **micrometeoroids** (a small IDP ($\lesssim$ 10 μm) that survives entry through Earth's atmosphere)

Meteorites
A meteorite is a macroscopic remnant of a rocky object from outer space that has landed on the surface of a planet or moon. Meteorites on the Earth usually result from the impact of asteroids of meter-sized or larger, as smaller objects tend to burn up completely in the atmosphere.


Meteoroid
Piece of cosmic debris, from microscopic dust up to 1 metre wide
Asteroid
Meteoroid larger than 1 metre wide
Fireball
Meteor at least as bright as Venus
Bolide
Exceptionally bright fireball that ends with an explosion
Meteor
Streak of light produced by meteoroid entering the atmosphere, either on its own (sporadic) or as part of a meteor shower
Meteorite
Asteroid or meteoroid that survives its trip to Earth's surface*
*Meteorite shown is NWA 1918-EUC, on display at Toronto's Royal Ontario Museum
Credit: NASA/ROM/Google/Scott Sutherland

Absolute Magnitude

It is defined differently than in other areas of astronomy. For asteroids, absolute magnitude H is defined as the apparent magnitude of the object under a hypothetical condition: the object is at 1 au from both the Sun and the observer, with a phase angle of α = 0°. Mathematically,

$$H = m - 5\log(r_{\mathrm{H}}\mathit{\Delta}) - \Phi(\alpha)$$

where $\boldsymbol{m}$ is the apparent magnitude, $\boldsymbol{r_{\mathrm{H}}}$ and Δ are the distances to the Sun and the observer in au, and $\Phi(\alpha)$ is the *phase function* that describes the phase-dependent reflectance of the object and is related to surface properties.

Absolute Magnitude

For **comets**, two magnitudes are used: the total magnitude $\mathbf{m_1}$, which refers to the brightness of the entire coma, and the nuclear magnitude $\mathbf{m_2}$, which refers to the brightness of the visible core region. Total magnitudes are more commonly used, as the definition of "nucleus" in the m_2 system can differ between observers and instruments. The absolute total magnitude, M_1, is defined as

$$M_1 = m_1 - 2.5n \log r_H - 5 \log \Delta - \Phi(\alpha)$$

where $\boldsymbol{n}$ is sometimes called the *activity index*. A larger n indicates a steeper brightening rate (brightening/fading faster). On average, comets have $n = 4$, although this value can vary significantly among different comets and across various activity phases for the same comet.

For **meteors**, absolute magnitude is defined as the apparent magnitude of the meteor corrected to an altitude of 100 km at the observer's zenith.

Asteroid-Comet Continuum

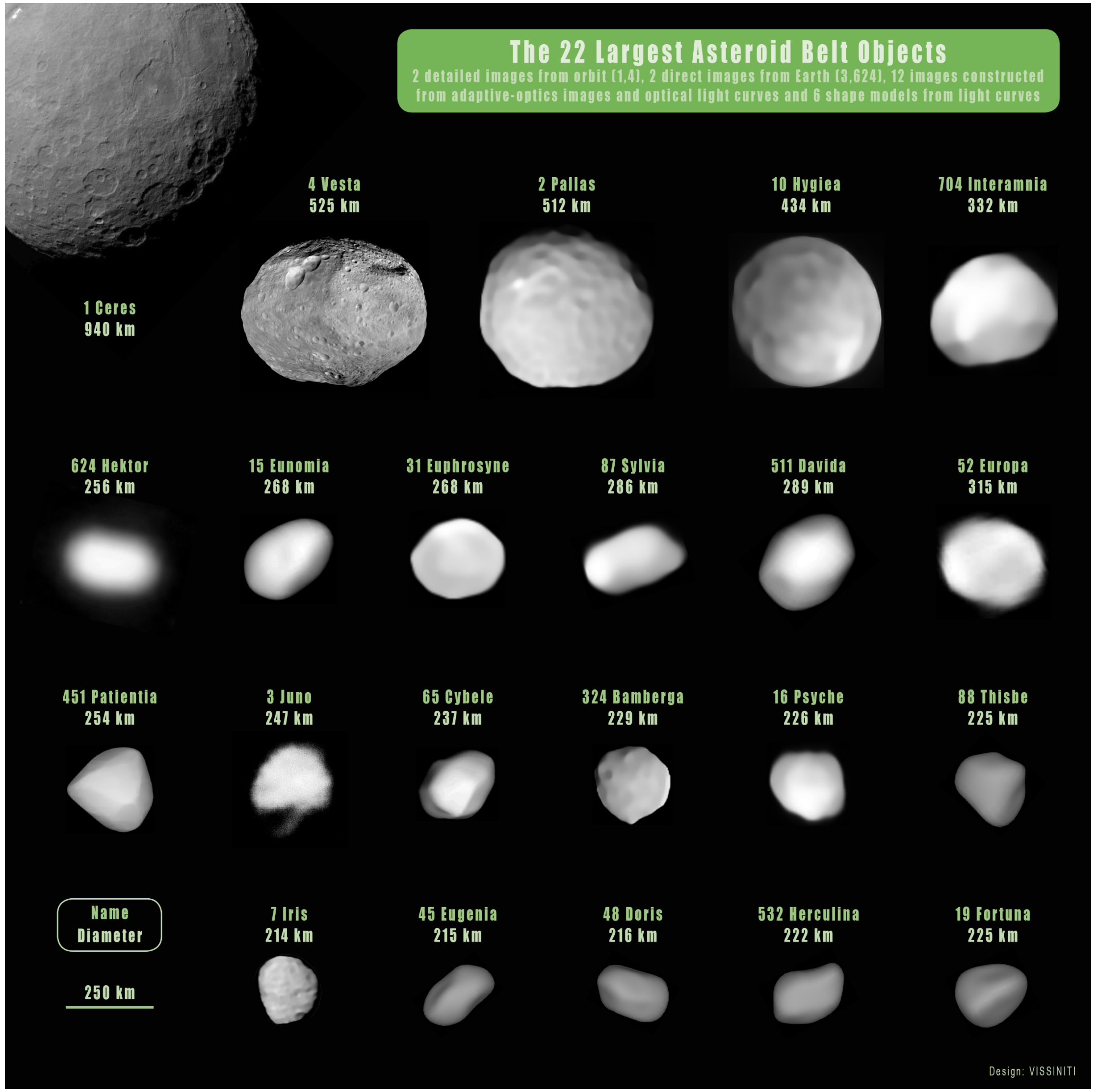
As the names suggest, **appearance** is a simple way to distinguish between asteroids and comets: asteroids appear star-like, while comets are fuzzy and sometimes exhibit a tail.
Asteroids and comets can also be classified based on their **compositions** or orbital **dynamics**:
Compositionally, comets contain ice, whereas asteroids do not; Dynamically, asteroids have near-circular orbits, while comets have very elongated and sometimes parabolic or hyperbolic orbits.

These three approaches (based on appearance, compositional, or dynamical properties) usually yield consistent results. However, a small number of objects discovered in recent years have challenged this paradigm. **Dual-status object** 133P/(7968) Elst-Pizarro, the first such outlier, was discovered as a main-belt asteroid but was found to exhibit a coma and a tail.

Objects on asteroid-like orbits that exhibit comet-like activity are known as **active asteroids**, while apparently inert objects on comet-like orbits are known as **asteroids on-cometary-orbits** (ACOs) and are sometimes presumed to be dormant comets.

The asteroid belt, also known the “main asteroid belt” or just “**main belt**”, is a torus-shaped region occupying the wide gap between the orbits of Mars and Jupiter.

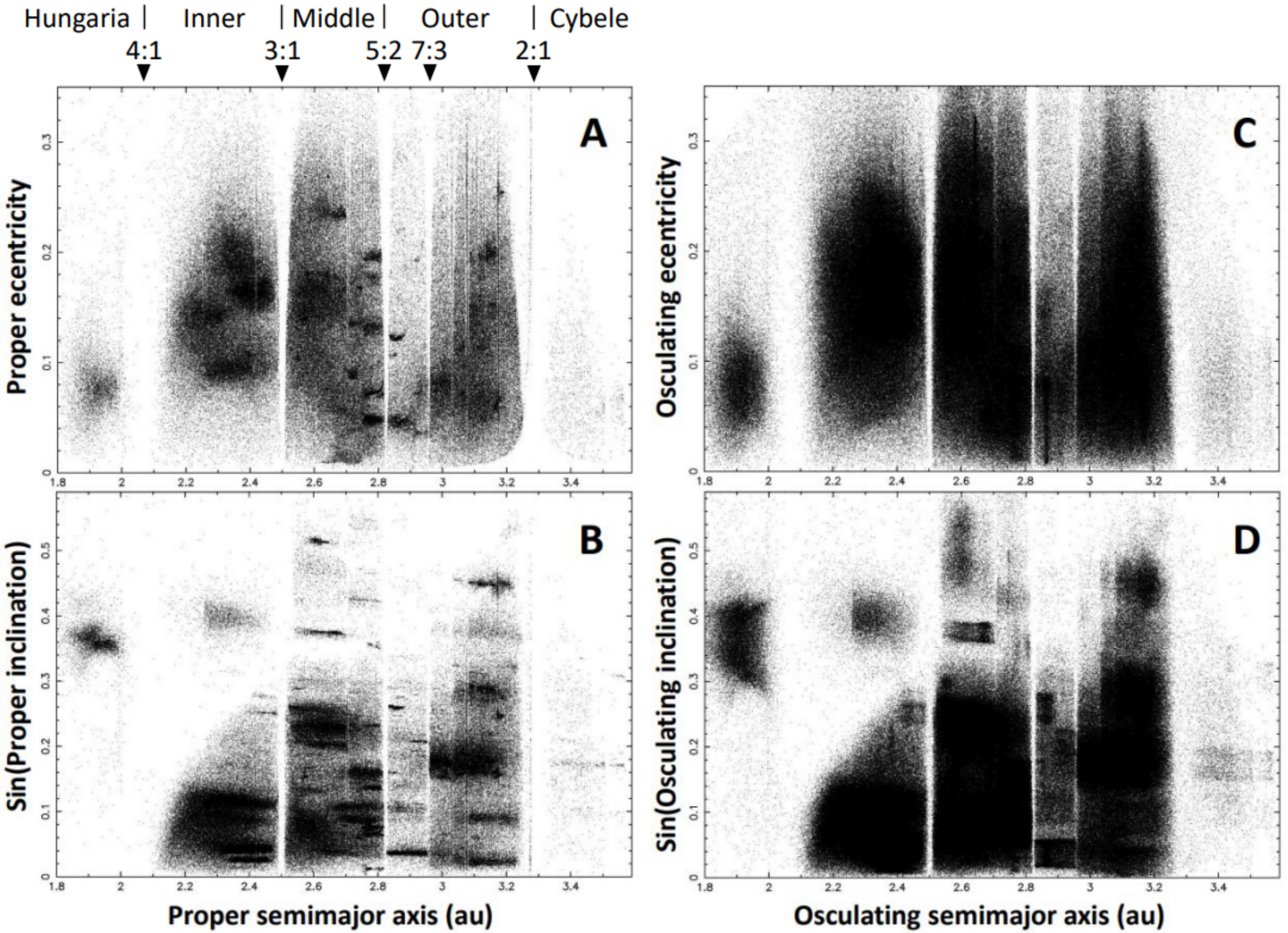
This region contains about **a million asteroids** that are 1 km or larger, with the dwarf planet (1) Ceres being the largest (D ~ 940 km) and most massive, containing 39% of the belt’s total mass. The total mass of the asteroid belt is estimated to be (1.8 ± 0.2) × 10−9M☉, or **0.06% of Earth’s mass**, and is dominated by the few largest objects.



Orbits: Kirkwood Gaps

Most main belt asteroids have low orbital eccentricities (**e < 0.4**) and semimajor axes between ~ **2.1 and 3.3** au. Main belt asteroids cluster in specific regions separated by the **Kirkwood gaps**.

These are narrow regions where orbital resonances with Jupiter quickly drive asteroids into high-eccentricity orbits, causing them to cross the orbits of terrestrial planets. A resonance region is denoted by a whole number ratio between the orbital periods of an asteroid in that region and Jupiter.



Composition (taxonomic systems)

Since asteroids do not emit visible light, reflectance spectroscopy is an important way for exploring their surface composition and properties. Since the 1970s, several taxonomic systems have been developed for optical spectrophotometry and spectroscopy (later extended into near-infrared) to classify asteroids.

These systems differ in the details, but all contain two broad classes: **“C” for carbonaceous objects, “S” for stony objects**, plus a number of smaller populations that cannot be categorized as either C- or S-type.

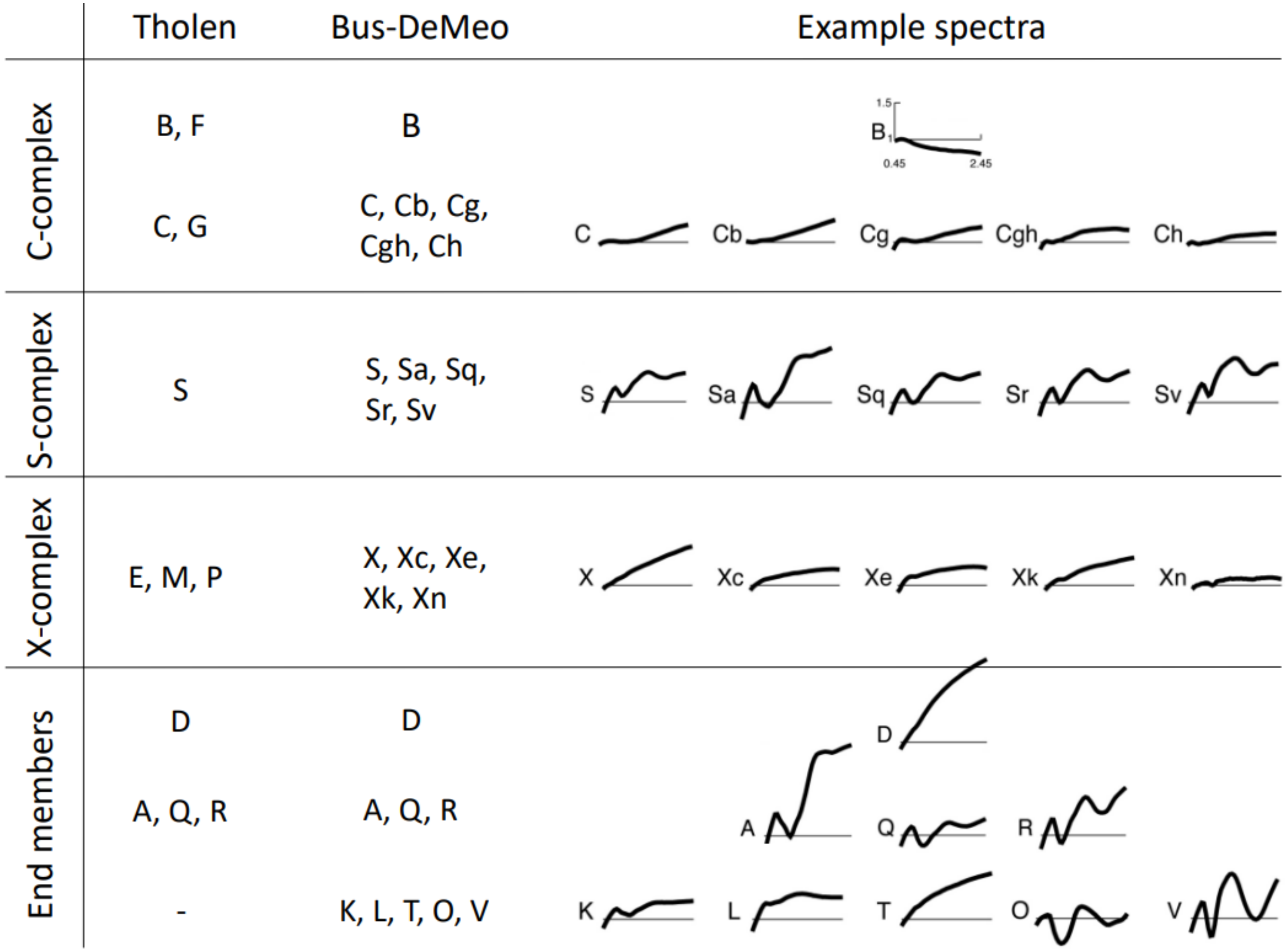


Figure 7 Summary of the Tholen (1989) and Bus–DeMeo (DeMeo et al., 2009) asteroid taxonomic systems. Compiled based on data from Cellino et al. (2002, Table 2) as well as the Bus–DeMeo classification website (http://smass.mit.edu).

Ⅲ. Populations 1. Asteroid Belt

Systematic spectroscopic surveys have revealed a prominent compositional trend in the main belt: **S-type** asteroids dominate the **inner** main belt, while **C-type** and other primitive asteroids dominate the **outer** main belt.

This trend is believed to reflect the conditions of the early Solar System, including the chemical and temperature gradient of the pre-solar nebula (DeMeo and Carry, 2014).

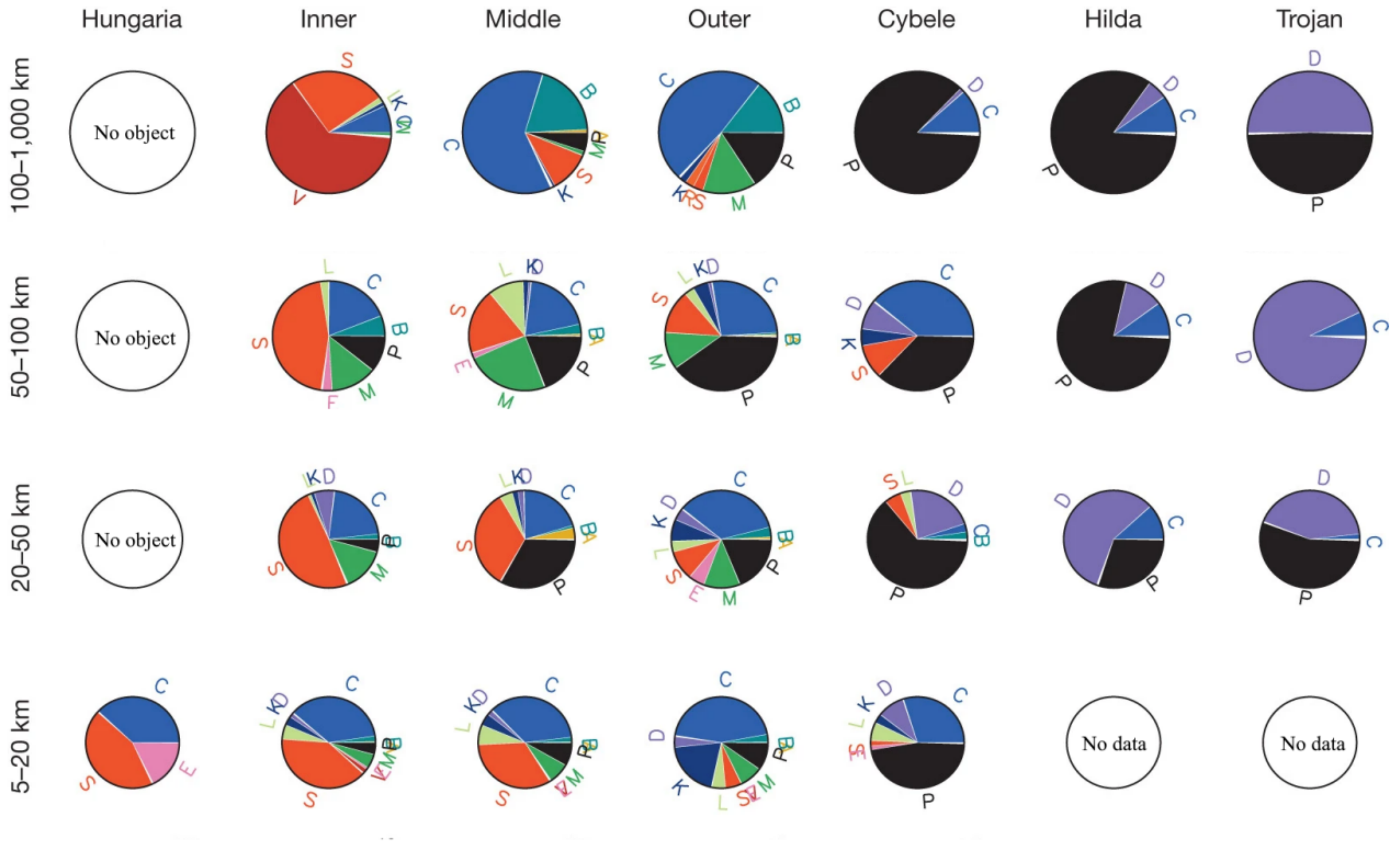


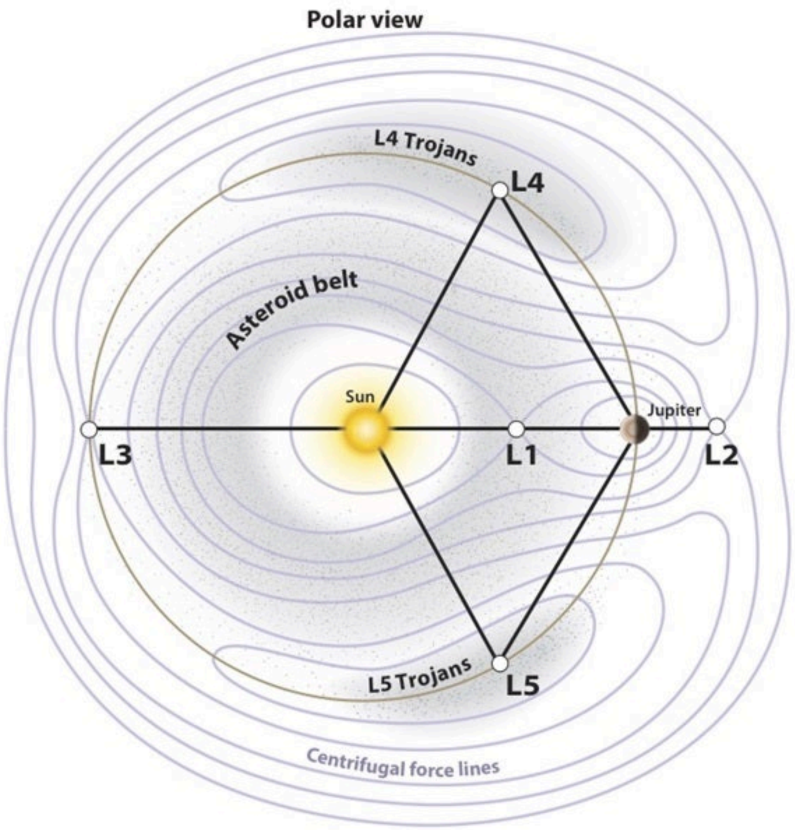
Figure 8 Distribution of various asteroid spectral types across the asteroid belt and the Trojans, categorized by size. Adapted from DeMeo and Carry (2014).

The Jupiter Trojans, often referred to simply as **Trojans**, are a group of asteroids that share the same orbit with Jupiter.
(The planets of Earth, Mars and Neptune also have their own Trojan population, but these are much smaller in size compared to Jupiter's Trojans.)

Trojans are located at Jupiter's stable Lagrange points: the **L_4 point**, which is 60° ahead of Jupiter in its orbit, and the **L_5 point** which is 60° behind.

Estimates suggest that the total mass of the Trojans is about **1/60th of the mass of the asteroid belt**.

A curious feature of the Trojans is that the number of L_4 Trojans is ~ 1.6× more than that of L_5 Trojans. This asymmetry may be linked to Jupiter's outward migration during the early Solar System (Li et al., 2023)



Ⅲ. Populations 3. Near-Earth Objects

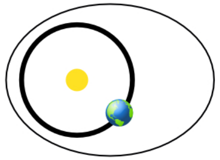
A Near-Earth Object (NEO) is an asteroid or a comet with a perihelion of < 1.3 au. Comets constitute less than 1% of the NEO population.(Similarly, an asteroid with a NEO orbit is known as a near-Earth asteroid (NEA).)

A specific subset of NEOs, known as Potentially Hazardous Objects (Asteroids) (PHOs/PHAs), pose a more direct threat to Earth. PHOs are defined as objects with a minimum orbit intersection distance (MOID) of < 0.05 au and an absolute magnitude of H < 22 (corresponding to a diameter of D $\gtrsim$ 140 m).

NEAs are further categorized into Amors, Apollos, Atens, and Atiras, based on their orbits relative to the Earth’s:

Amors

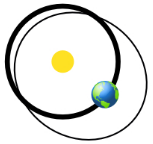
Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid (1221) Amor)



$a > 1.0$ AU
1.017 AU $< q < 1.3$ AU

Apollos

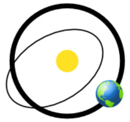
Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid (1862) Apollo)



$a > 1.0$ AU
$q < 1.017$ AU

Atens

Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid (2062) Aten)



$a < 1.0$ AU
$Q > 0.983$ AU

Atiras

NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid (163693) Atira)

$a < 1.0$ AU
$Q < 0.983$ AU

(q = perihelion distance, Q = aphelion distance, a = semi-major axis)

Impact Risk

The Chelyabinsk event in 2013: the largest impact event on Earth in over 100 years, was caused by a 18-m-sized asteroid approaching from the sunward direction.

As of 2024, more than 30,000 NEOs have been discovered and cataloged. The first successful prediction of an asteroid impact occurred in 2008 with asteroid 2008 TC3. Since then, another seven NEA impacts have been predicted before they occurred.

Efforts are ongoing to understand how to prepare for and potentially prevent destructive impacts. (DART mission in 2022)

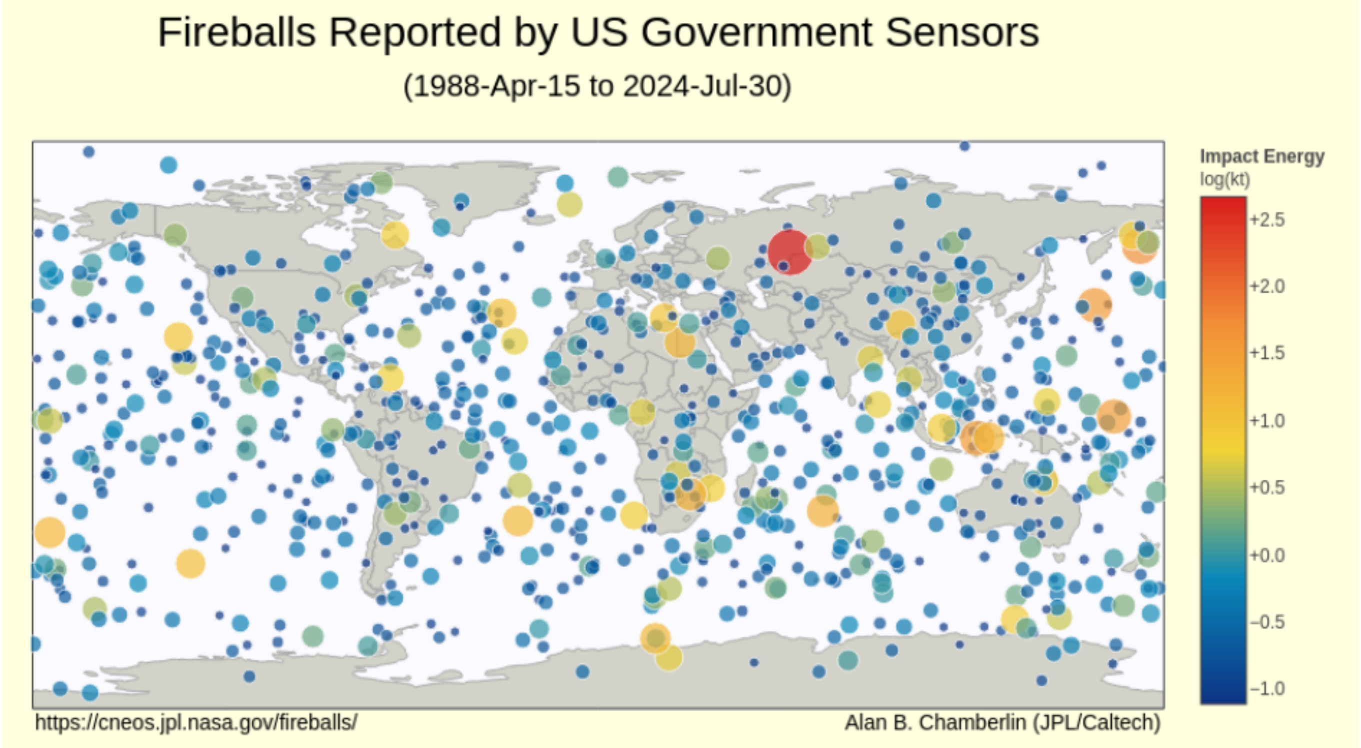


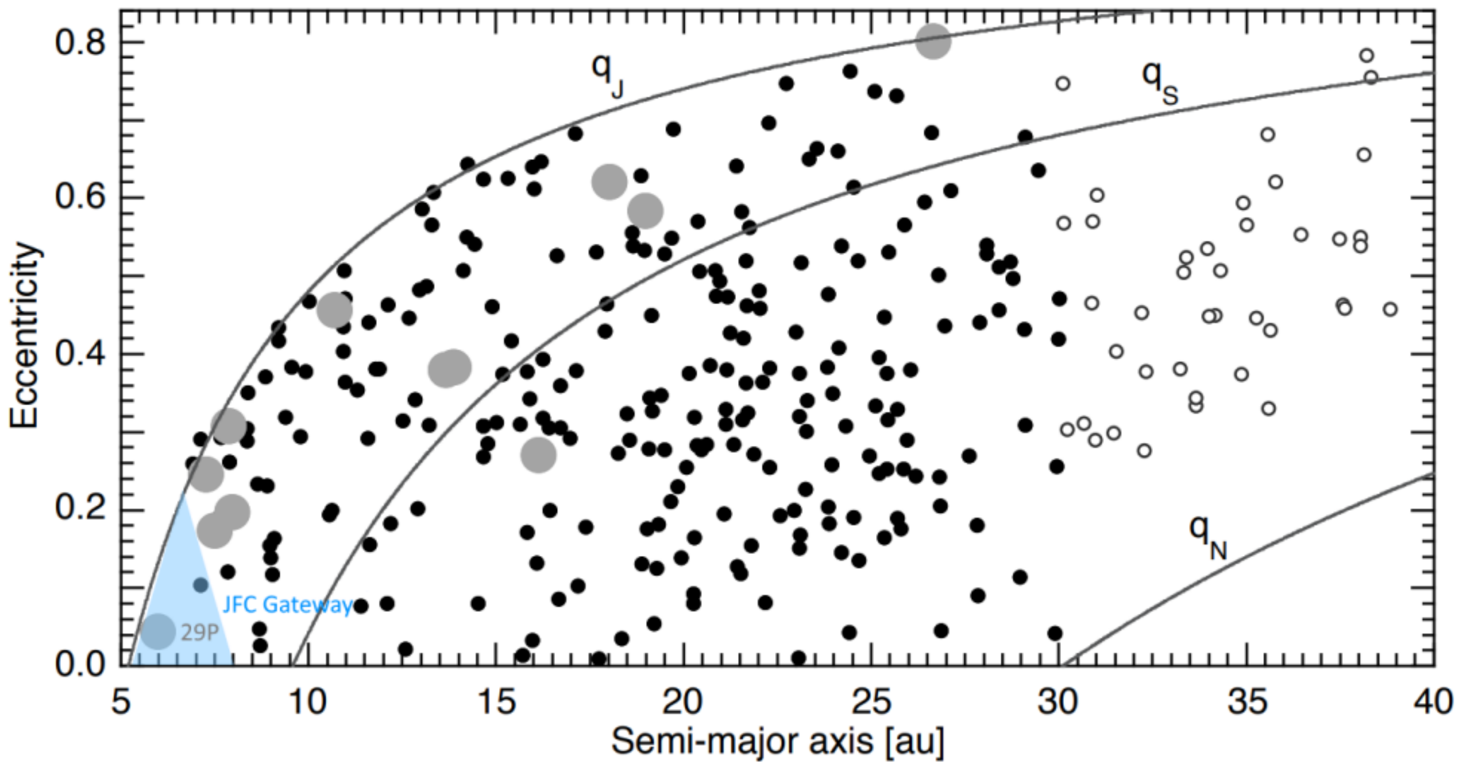
Figure 10 Bolides and fireballs detected by geostationary satellites between 1988 and 2024. The largest data point in red is the 2013 Chelyabinsk event.

Centaurs are small bodies that orbit the Sun between the orbits of Jupiter and Neptune. They are **ice-rich** objects originated from the trans-Neptunian region perturbed into the planetary region.

Recent estimates suggest there are ~ 10 Centaurs with diameters of 100 km or larger, corresponding to a total population mass of ~ 1% of the asteroid belt.

The MPC defines Centaurs as any object with q > 5.2 au and a < 30.1 au, whereas 5.2 au and 30.1 au are the semimajor axes of Jupiter and Neptune.

The *a* − *e* distribution of known Centaurs.



A comet in its raw form consists only of a nucleus composed of **rock, ice, and dust**, which is typically a few km in size. Comets are generally classified into two broad categories: short-period comets and long-period comets.

Short-Period Comets (SPCs)

Short-period comets (SPCs) have orbital periods P < 200 yr. They are further divided into Jupiter-family comets (JFCs) and Halley-type comets (HTCs). Traditionally, JFCs and HTCs are classified based on their orbital periods: JFCs have P < 20 yr and HTCs have 20 < P < 200 yr. As of 2024, about 950 SPCs have been cataloged.

Long-Period Comets (LPCs)

LPCs are comets with P > 200 yr. Comets on parabolic (e = 1) or hyperbolic orbits (e > 1) are sometimes referred to as non-periodic comets. As of 2024, more than 600 LPCs (including non-periodic comets, excluding comet fragments) have been cataloged.

6. Interplanetary Dust Cloud

The **interplanetary dust cloud**, also known as the zodiacal cloud, is an extended, disk-like structure that spans the inner Solar System. It stretches from the innermost Solar System out to just beyond Jupiter's orbit.

At 1 au from the Sun, the volume density of particles of μm-sized or larger is ~ 10^{-4} m^{-3} . The interplanetary dust cloud is a significant source of foreground contamination across nearly all targets of observational astronomy, affecting wavelengths from optical wavelengths to far infrared.

In addition to the dust "background", the interplanetary dust cloud also includes dust trails or meteoroid streams from comets, as well as particles from active asteroids and recent collisions that have created asteroid families

Ⅳ. Summary

• Small bodies can answer big questions:
- They offer profound insights on the formation and evolution of our Solar System;
- the origin of water and potentially life on Earth;
- offer a unique perspective on similar structures observed in exoplanetary systems.

Additionally, studying NEOs helps us understand potential threats to Earth and explore ways to mitigate possible impacts.

• A wide range of techniques have been developed and employed to study small bodies, including Earth- and space-based telescopic observations, theoretical modeling, in-situ exploration with spacecraft, laboratory analysis of meteorites, returned samples, as well as observations of meteors and related phenomena.

• The future of small body science is promising:
LSST, NEO Surveyor mission, 30-m-class telescopes …

• Several spacecraft missions have or will soon embarked to explore small bodies:
Lucy mission, OSIRIS-APEX and RAMSES, Psyche mission and Tianwen-2, DESTINY+ …

Thanks