What is the best way to tell how old the solar system is?

By studying rocks!

Rocks from where?

Anywhere we can find them as long as they are old!

To date:
- Earth rocks - we are here so easy
- Lunar rocks - we went there and collected them
- Mars rocks - some hit the Earth after being blasted off Mars
- Meteorites - they hit the Earth and we collect them
- Space particles - we collect them with spacecraft

How do we tell the age of a rock or particle?

By looking at its isotopic composition!

Brown are protons – always 8 so an the nucleus of an oxygen atom
Green are neutrons – number can vary making different isotopes

Beta decay (Rubidium – Strontium dating)

Alpha decay (Uranium – lead dating)
<table>
<thead>
<tr>
<th>Parent Isotope</th>
<th>Daughter Isotope</th>
<th>Half-life (millions of years)</th>
<th>Decay Constant (yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>$^{40}$Ar</td>
<td>1,250</td>
<td>$5.81 \times 10^{-11}$</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>$^{87}$Sr</td>
<td>48,800</td>
<td>$1.42 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

Potassium (K) has 19 protons, Argon (Ar) 18 so Beta decay via capture of an electron by the nucleus converting a proton to a neutron.
Rubidium (Rb) has 37 protons, Strontium (Sr) has 38 so Beta decay by losing an electron from nucleus converting a neutron to a proton.

**Oldest rocks on Earth are:**

**Acasta Gneisses** in northwestern Canada near Great Slave Lake (4.03 billion years) – Gneisses are sedimentary or igneous rocks that are heavily modified by high temperatures and pressures. The Acasta Gneisses are granitic igneous rocks that have been metamorphosed.

**Isua sedimentary rocks** in West Greenland (3.7 to 3.8 billion years)

**Zircon crystals** with Uranium – Lead ages of 4.4 billion years have recently been reported from younger sedimentary rocks in west-central Australia.

From USGS (2007)

Cleaned exposures of the Acasta gneisses at their discovery site. Ancient tonalites (an igneous plutonic intrusive rock) (4.03 billion years) occur on left side of the picture, and are intruded by highly deformed younger granite sheets and mafic dykes.
The 4.4 billion year old Zircon crystal (ZrSiO₄ – Zerconium silicate) found in the Jack Hills area of Western Australia. Rocks in which it was found are only about 3.7 billion years old. Crystals contain small amounts of Uranium and Thorium that can be dated. The oxygen isotopic composition implies that the crystal formed at low temperature in the presence of water – casts doubt on origin of Moon.

Outcrop of metamorphosed sedimentary rock in Western Australia where zircon crystal was found. Crystal originated from granitic igneous rocks.

EARTH ROCKS AND CRYSTALS PLACE A LOWER LIMIT ON THE AGE OF THE SOLAR SYSTEM OF ~ 4.4 BILLION YEARS

SOME METEORITES DATE FROM THE FORMATION OF THE SOLAR SYSTEM – DATING THEM GIVES THE BEST AGE

Mező-Madaras, Romania, ordinary chondrite. This close-up of a cut and polished face of Mező-Madaras measures ~ 7 cm from left to right. Chondrites are named for the nearly spherical, silicate-rich objects they contain called chondrules, which were among the first objects to have formed in our solar system. As is evident in this picture, Mező-Madaras has abundant large chondrules. Photo by D. Ball, ASU.
Allende, Mexico, carbonaceous chondrite. This chondrite also contains chondrules (note the round cavity left by the removal of a large chondrule). In addition, Allende, like many carbonaceous chondrites, contains calcium-aluminum-rich inclusions (CAIs). Unlike chondrules, which are round and composed mostly of silicate minerals like olivine and pyroxene, CAIs are predominantly white to light gray in color, irregularly shaped, and rich in refractory (high-temperature) minerals like melilite and spinel. They are believed to pre-date chondrules by at least 2 million years. This specimen is ~ 11 cm from left to right. Photo by D. Ball, ASU.

Johnstown, CO, diogenite. Diogenite achondrites are primarily composed of orthopyroxene, a silicate mineral (indicating high temperature processing). Johnstown is brecciated and contains large orthopyroxene grains in a groundmass of crushed and broken orthopyroxene. This specimen is ~ 13 cm long. Photo by D. Ball, ASU.

Albin, WY, pallasite. Pallasites are stony-iron meteorites composed of about half metal and half olivine, a greenish silicate mineral. This slice, which is ~ 18 cm long, has been illuminated from behind to distinguish its olivine from the surrounding metal. Photo by D. Ball, ASU.

Rancho Gomelia, Mexico, octahedrite. This iron meteorite has been cut, polished, and etched with acid on one face to reveal an interlocking crystal structure of variable composition nickel-iron alloys. This pattern, called the "Widmanstätten" pattern, is unique to the subgroup of iron meteorites called octahedrites. The etched face is ~ 14 cm from bottom to top. Photo by D. Ball, ASU.
Lunar rock – a meteorite

Meteorite from Mars – found in Antarctica

Small meteorite still buried in wind ablated blue ice at the Allen Hills site.

Allen Hills rock outcrop south of the Ross ice shelf.

Antarctic meteorite finds

How it works!

Meteorite Types & Percentage that Falls to the Earth

**Stony meteorites (92.8%)**
- Chondrites (85.7%) From the planetary nebula. 4.55 billion years old. With spherules in mm size range (chondrules).
- Carbonaceous. Contains carbon compounds. Enstatite. Contains MgSiO3
- Achondrites (7.1%) Tectonically processed of varying age. Without spherules.
  - HED group. From asteroid Vesta.
  - SNC group. From Mars.
  - Aubrites.
  - Ureilites

**Stony iron meteorites (1.5%)** From mantles and cores of asteroids?
- Pallasites
- Mesosiderites

**Iron meteorites (5.7%)** From cores of asteroids?
Which meteorite type most useful for dating the age of the solar system?
Clearly Chondrites and Carbonaceous Chondrites – composition same as that of the Sun (except for gases like hydrogen and helium)
Spherical Chondrites and CAI inclusions are oldest

There are three daughter isotopes of Uranium and Thorium; they are $^{206}\text{Pb}$, $^{207}\text{Pb}$, and $^{208}\text{Pb}$ (lead isotopes). $^{204}\text{Pb}$ is the only non-radiogenic lead isotope; therefore is not one of the daughter isotopes. These daughter isotopes are the final decay products of U and Th decay chains beginning from $^{238}\text{U}$ (half-life ~4.4 billion years), $^{235}\text{U}$ (half-life 704 million years) and $^{232}\text{Th}$ (half-life ~14 billion years) respectively. With the progress of time, the final decay product accumulates as the parent isotope decays at a constant rate. This shifts the ratio of radiogenic Pb versus non-radiogenic $^{207}\text{Pb}$ ($^{207}\text{Pb}$/$^{204}\text{Pb}$ or $^{206}\text{Pb}$/$^{204}\text{Pb}$) in favor of radiogenic $^{207}\text{Pb}$ or $^{206}\text{Pb}$.

Amerin et al, Science, 297, 1678-1683, 6 Sept 2002
Apollo astronaut on the Moon

Soviet Lunar Rover

Ages of lunar rocks from Rb-Sr isotopic dating

SPACE PARTICLES

Sample particles from comets
STARDUST Mission to Comet Wild 2.
Flyby Jan 2, 2004
Return to Earth, Jan 15, 2006

COMETS
MAJOR SURPRISE – Comet Wild 2 has no unmodified particles

All the particles were formed in the inner solar system and somehow transported to the outer solar system.

If this is true for all cometary material it is a major problem for our ideas about the formation of the solar system.