Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets contributed to Earth’s atmosphere


The origin of cometary matter and the potential contribution of comets to inner-planet atmospheres are long-standing problems. During a series of dedicated low-altitude orbits, the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the Rosetta spacecraft analyzed the isotopes of xenon in the coma of comet 67P/Churyumov-Gerasimenko. The xenon isotopic composition shows deficits in heavy xenon isotopes and matches that of a primordial atmospheric component. The present-day Earth atmosphere contains 22 ± 5% cometary xenon, in addition to chondritic (or solar) xenon.

Comets are among the most pristine solar system materials (1). Their abundant volatile species, mainly in the form of ices, are intimately mixed with refractory silicate-rich phases and organics, the origins of which—either in the protosolar disk or interstellar medium—are still under debate (1). The discovery that Comet 81P/Wild contains high-temperature minerals akin to those found in primitive meteorites with key isotopic signatures (e.g., that of oxygen) typical of solar system reservoirs (2) suggests that some of the cometary constituents were cycled close to the proto-Sun and were radially transported outward. However, the case of ice is less clear. Enrichments in deuterium and nitrogen-15 in comets (3, 4) have been regarded as either originating from processing in the disk outskirts under irradiation or resulting from low-temperature ion-molecule reactions in molecular clouds. Another unresolved problem is the possible contribution of comets to inner-planet atmospheres. Although the D/H and 15N/14N signatures of the terrestrial atmosphere and oceans suggest an inner solar system origin for volatile elements on Earth (5), variations in the D/H ratio in primitive meteorites point to the contribution of interstellar water to asteroids (6).

Xenon, the heaviest stable noble gas, with nine isotopes of different nucleosynthetic origin (7, 8), is a key element for identifying nuclear components present in presolar material. The composition of solar system Xe, represented by measurements of the solar wind (7), is the result of the homogenization of such components. Several radioactive decays also produce Xe isotopes, among which that of 129I (half-life of 15.6 million years) decaying into 129Xe provides time constraints on the early evolution of the solar system. Earth’s atmosphere has a xenon composition that is unique among solar system objects and reservoirs (9). It is depleted relative to expectations based on the extrapolated behavior of the lighter noble gases Ne, Ar, and Kr, by a factor of ~20 relative to Kr (normalized to the abundance in chondritic meteorites). Atmospheric Xe is also isotopically (mass-dependently) fractionated, being enriched in heavy isotopes by 30 to 40 per mil per atomic mass unit (u) compared with chondritic xenon (hereafter, Q-Xe) or solar wind xenon (hereafter, SW-Xe); this is known as the xenon paradox (10). When corrected for mass-dependent isotopic fractionation (MDF), atmospheric Xe does not directly correspond to any known solar system component. These observations have led to the definition of a theoretical primordial component termed U-Xe (9) (where U stands for Uluru, the German word for primordial, and not for uranium-derived fission Xe). U-Xe is close to SW-Xe for the 131–136Xe isotopes but is depleted in the heavy Xe isotopes, particularly 134Xe and 136Xe. U-Xe has not been clearly identified in meteorites or planetary samples.

We report the determination of the isotopic composition of xenon in a comet. Xenon isotopes were measured with the Double Focusing Mass Spectrometer (DFMS) of the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) instrument suite (11) on the Rosetta spacecraft. DFMS is a high-mass-resolution instrument (mass divided by change in mass = 3000 at 1% peak height at a mass/charge ratio of 28 u/e) that measured gases emitted by comet 67P/Churyumov-Gerasimenko (67P/C-G), presumably from sublimation of ice (3). The Xe measurements were carried out during a series of dedicated low-altitude orbits, between 10 and 7 km from the comet’s center of mass, from 14 to 31 May 2016 (12). Because of the high resolution of DFMS, mass/charge ratios of 129, 131, 132, 134, and 136 u/e were essentially free of interfering species of similar mass, as confirmed by the shapes of the peaks, whereas interference presumably due to S1+ was detected at mass/charge = 128 u/e and corrected using peak deconvolution (12). A slight contribution of a few percent at mass/charge = 130 u/e, due to S1+-containing 34S, was also corrected. The average Xe isotope ratios were derived from this database, with uncertainties corresponding to 1 standard deviation (σ) of the mean. The ROSINA instrument was equipped with a gas calibration unit that permitted in-flight analysis of reference gases, including xenon (12).

Figure 1 shows the xenon composition of 67P/C-G, normalized to that of the solar wind (horizontal orange line) and to 132Xe (the most abundant Xe isotope in most cases), together with other solar system compositions (terrestrial atmosphere and chondritic). The data obtained from the in-flight calibration runs are consistent with a terrestrial Xe composition, as expected, but the 67P/C-G Xe isotopic ratios deviate markedly from solar, or chondritic, values. Whereas 128Xe/132Xe, 130Xe/132Xe, and 132Xe/134Xe are solar-like within uncertainties, 67P/C-G Xe is strongly depleted in 132Xe and 134Xe, by ~40 and ~60%, respectively.

We first tested the possibility that the observed variations are due to MDF, in which case the data should align along the dotted curve of Fig. 1. The 130–132Xe/134Xe ratios could be reasonably accounted for by MDF affecting a solar-like Xe component. The required fractionation factor, however, should be extremely high, around 14% per atomic mass unit, higher than ever observed for Xe (or other noble gases) in any solar system object or reservoir. Notesto et al. (13) found no evidence for Xe isotopic fractionation upon trapping in water ice, and trapping of ionized Xe results in a MDF of no more than 1% (14). Alternatively, MDF could also be due to distillation enhancing isotopic fractionation during loss of Xe isotopes from a reservoir (e.g., cometary ice). To produce...
Cometary noble gases are concentrated in ice (13, 19, 20), and a presolar origin for Xe would imply that cometary ice is also presolar. Such an origin is in agreement with the detection of abundant O$_2$ (1 to 10% relative to H$_2$O) released on June 27, 2017 http://science.sciencemag.org/ Downloaded from
A 22 ± 5% contribution of comets to atmospheric Xe also reproduces the 6.8 ± 0.3% (1σ) 129Xe excess observed in the atmosphere (Fig. 4). This excess, classically attributed to the decay of radioactive 129I trapped in the growing Earth, has previously allowed researchers to set time constraints on the accretion of Earth and the development of its atmosphere (17). Degassing of mantle Xe containing radiogenic 129Xe through geological periods of time also contributed 129Xe to the atmosphere, but probably no more than ~1% (12). Thus, a large fraction of the monoisotopic 129Xe excess in the terrestrial atmosphere may be inherited, implying that the 129I-129Xe system as a geochronological tool should be reconsidered and that the Wetherill’s retention time of ~100 million years after the SSSF (17) should be seen as a lower limit. It remains unclear whether inherited cometary 129Xe is consistent with the presence in the present-day Earth atmosphere of a component derived from the fission of 244Pu.

REFERENCES AND NOTES
12. Materials and methods are provided as supplementary materials.

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We acknowledge the work of the whole ESA Rosetta team. ROSINA data are publicly available at ESA’s Planetary Science Archive at www.cosmos.esa.int/web/psa/rosetta and NASA’s Planetary Data System at https://pdsplanetary.pdsciences.org/missions/rosetta/index.shtml. M.R. and K.A. performed data reduction. M.R., K.A., and B.M. analyzed the data. B.M. interpreted the data and wrote the paper. K.A., M.R., and H.B. contributed to data interpretation and the supplementary materials. All authors contributed to the ROSINA instrument and commented on and revised the manuscript.

SUPPLEMENTARY MATERIALS
www.sciencemag.org/content/356/6342/1069/suppl/DC1
Materials and Methods
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Figs. S1 to S5
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References (27–36)
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Comets contributed to Earth’s atmosphere

Models of xenon’s origin in Earth’s atmosphere require an additional, unknown source that has been a mystery for several decades. Marty et al. measured isotopic ratios of xenon released from comet 67P/Churyumov-Gerasimenko and found that they match the heretofore unknown source. The xenon appears to have been trapped in ice within the comet since before the solar system formed. Comets contributed about a quarter of the xenon on Earth, which constrains the amount of other materials (such as water) delivered to our planet by comets.

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