

Instruments of Cosmochemistry

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Ion Microprobe

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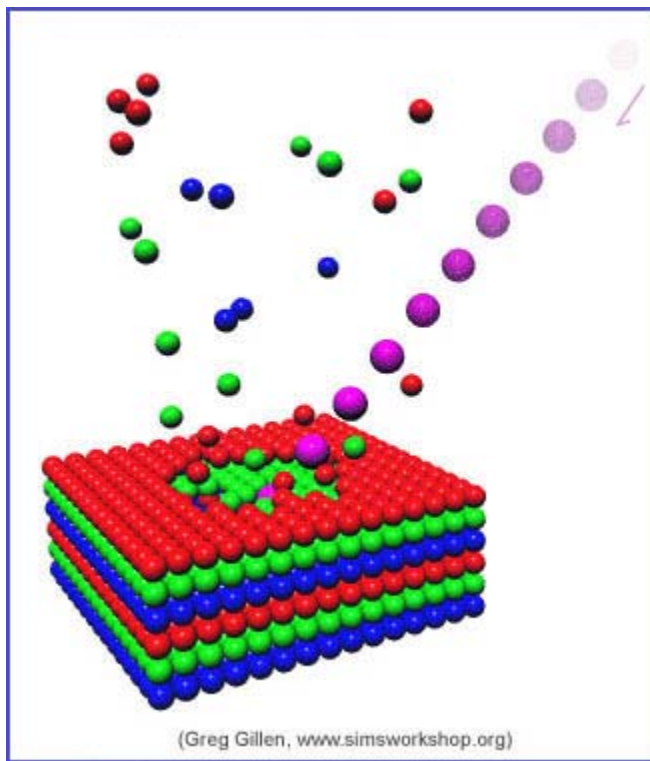


In this series of articles, "Instruments of Cosmochemistry," PSRD highlights the essential tools and amazing technology used by talented scientists seeking to unravel how the solar system formed. You will find information on how the instruments work as well as how they are helping new discoveries come to light. 💡

Precision Instrument

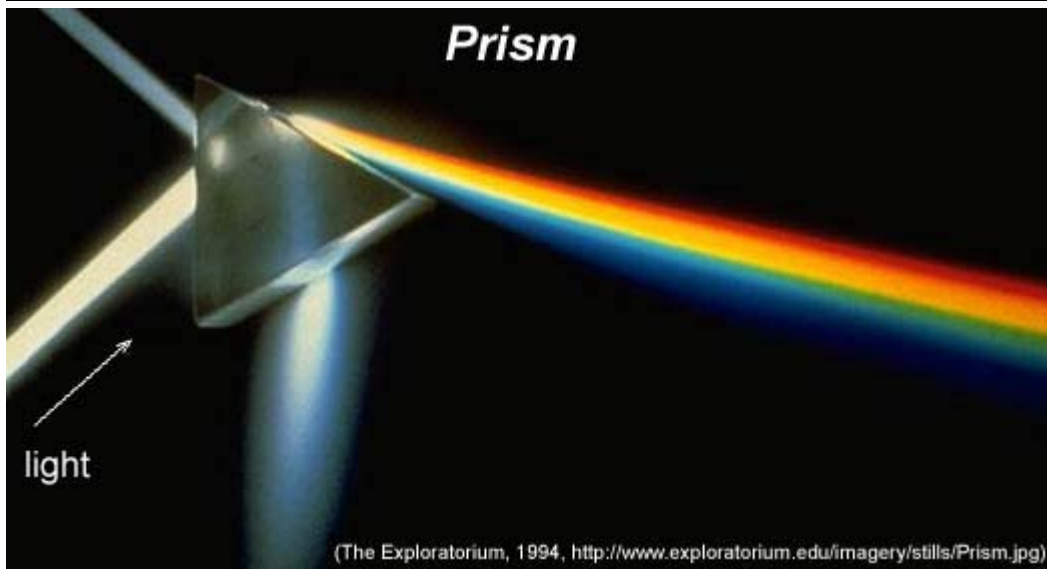
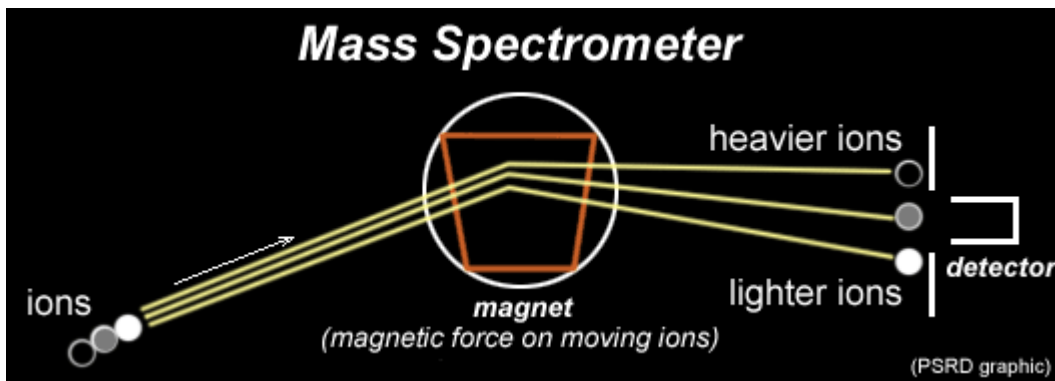
The ion microprobe is a Secondary Ion Mass Spectrometer (SIMS), a precision instrument used to quantitatively analyze the elements and [isotopes](#) of materials at microscopic scales. This complicated instrument consists of an ion source, mass spectrometer, detection system, associated electronics, and vacuum system. A schematic diagram of an ion microprobe is presented later, but first we'll look at the instrument's use of a primary ion beam to bombard a sample of material and how that gives us information about the material's composition.

In SIMS analysis, a primary, high-energy beam of ions (usually oxygen, argon, or cesium) is aimed at a small area of a sample, such as a mineral grain. The primary ions have energies on the order of 10,000 electron volts. (An electron volt is the energy given to an electron by accelerating it through 1 volt of electric potential difference. The electrons in a typical television screen ... not the new flat-screens... have about 20,000 electron volts.) The primary ions dig a hole into the sample causing sputtering of atoms and ions (called secondary ions) that reveal the elemental and isotopic characteristics of the sample. See graphic below.



Artist's rendition of an incoming beam of ions (colored purple) impacting a sample and sputtering off the upper few layers of particles (colored red, green, and blue) some of which are ions.

These secondary ions (approximately 1% of the sputtered material) are accelerated into a mass spectrometer, where they are sorted by mass/charge ratios with a large sector magnet. See diagram below.

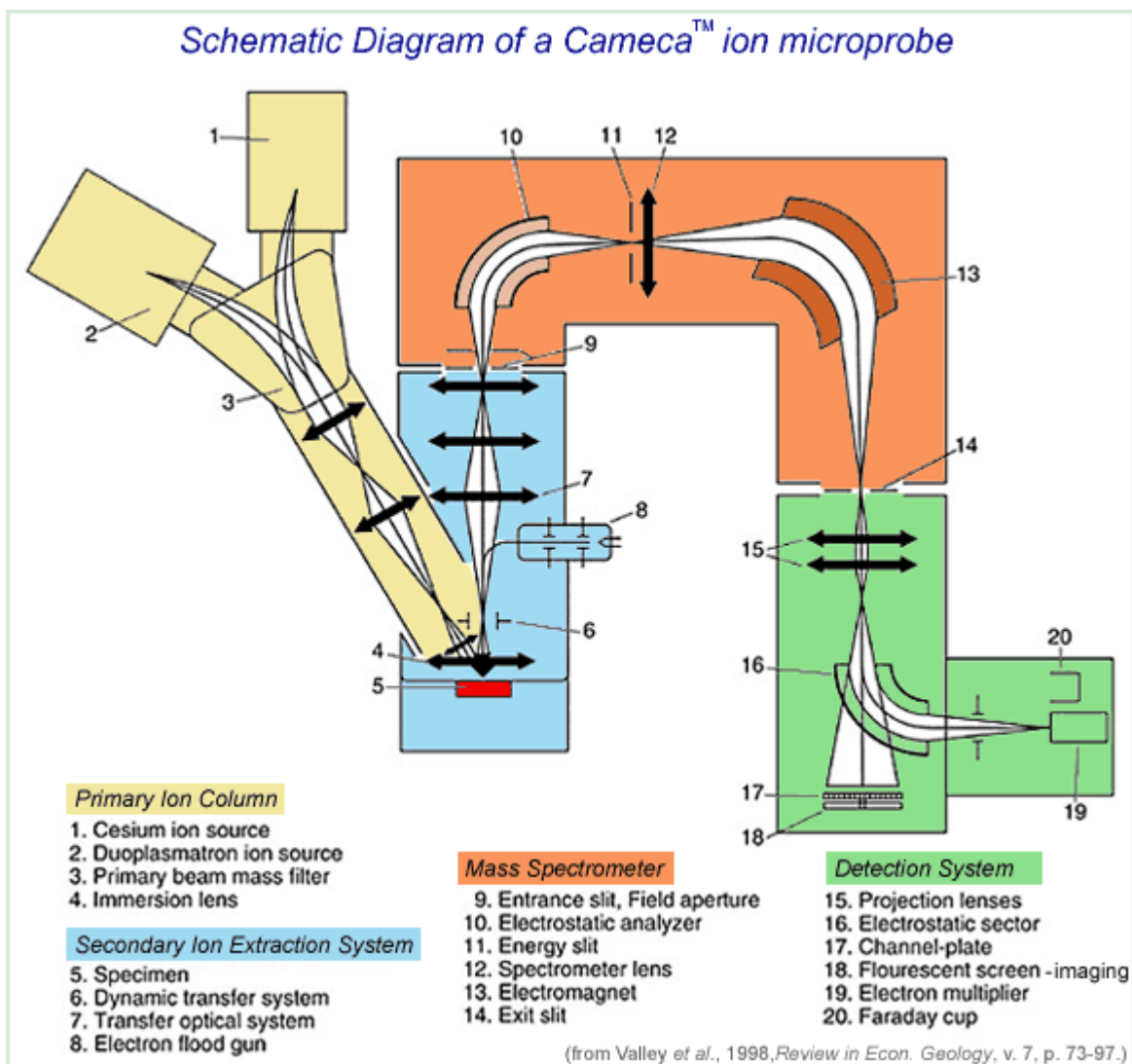


TOP: In a mass spectrometer, ions travel different paths through the magnet to the

detector due to their mass/charge ratios. A mass analyzer sorts the ions according to mass/charge ratios and the detector records the abundance of each ratio. BOTTOM: For an analogy, think of how a prism refracts and scatters white light separating it into a spectrum of rainbow colors.

A series of ion detectors counts the ions in different mass categories. Analysts take these raw counts, apply corrections, and normalize them to well-analyzed standards to arrive at the true abundances of elements and isotopes in the original sample. (Read an account of SIMS in use in PSRD article: [A New Type of Stardust.](#))

The diagram, below, shows the entire instrument scheme.



The different components of an ion microprobe are numbered and color-coded in this diagram. Ion beam paths are shown in white. Starting from the left, the primary ion column (yellow) provides the highly-focused ion beam produced from one of two sources (1,2). The sample (5, red) is located where the primary ion column joins the secondary ion extraction system (blue) wherein lenses focus the sputtered secondary ions into the mass spectrometer entrance slit (9, orange). The secondary-ion mass spectrometer (orange) is a double focusing mass spectrometer with both electrostatic and magnetic sectors. The electrostatic analyzer (10) bends lower energy ions more strongly than higher energy ions. The ions then pass through the electromagnet sector (13) where lower mass ions are bent more than higher mass ions. Finally, the secondary ions pass to the sensitive detection systems (green), which include an electron multiplier for counting individual ions (19), and Faraday cup for measuring ion current (20). Cameca™ ims-series ion microprobes also have the capability to operate in "ion microscope" mode, providing elemental and isotopic imaging capability at ~1 micrometer spatial resolution. The images are captured by an imaging device consisting of a channel-plate (17) and a fluorescent screen (18) in the detection system.

SIMS analysts may choose to vary several features of the instrument: (1) the polarity and species of the primary ion beam (O^- , O^{2+} , Ar^+ , Cs^+ are often used), (2) the impact energy (between $\sim 3,000$ - $20,000$ electron volts), current, and diameter of the primary ion beam, (3) the polarity of the secondary ion beam, and (4) the initial kinetic energies of the secondary ions detected.

SIMS Virtues

SIMS allows the study of microscopic grains in their native habitat. Unlike other types of mass spectrometers, the ion microprobe makes the *in situ* measurements on polished natural samples, so the mineralogical context of the grains remains intact. For a cosmochemistry example, see **PSRD** article: [Silicate Stardust in Meteorites](#). In the case of many extraterrestrial samples the grains are, in fact, so small that it is physically impossible to separate them for standard mass spectrometric analysis. So, the use of SIMS analysis eliminates the need to physically segregate grains from a sample.

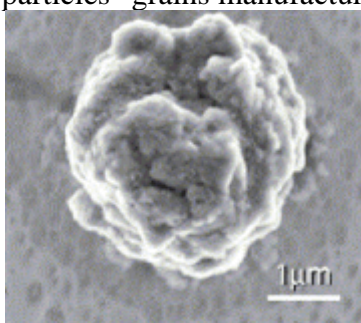
An ion microprobe can measure isotope ratios with a precision of a part per thousand or trace-element abundances at the part per million to part per billion level, while retaining the mineralogical context on a microscopic scale. The newest instruments, such as the Cameca™ 1280 ion microprobe, allow cosmochemists to image the micro-distributions of elements and isotopes at a sub-micrometer spatial scale. This allows isotope ratio measurements on very small samples, such as sub-micrometer presolar grains or comet samples returned by NASA's Stardust mission.

One of the features that permits a modern SIMS to analyze and image small grains in place in a rock is its impressively high mass resolving power. This parameter is expressed as the ratio of the mass of an ion to the difference between two masses that can be separated. The latest version of the Cameca™ SIMS, for instance, has a mass resolving power of 6000 routinely (which is required for separating $^{17}O^-$ from an interference $^{16}OH^-$ peak), but may be capable of a mass resolving power of up to 25,000. This minimizes the overlap between two peaks being measured, allowing measurements of elements that were not previously accessible by ion microprobe.

Cosmochemical Applications using the Ion Microprobe

Whenever new instruments or sharp improvements in analytical techniques have come along they have led to startling new discoveries in cosmochemistry. The ion microprobe is no exception. In fact, it might be the poster instrument for showing how a new technique can change the way we look at the universe.

PSRD has described discoveries in several areas of cosmochemistry that rely on use of the ion microprobe (see listing in next section). One of the most amazing of these is the study of pre-solar grains in meteorites and interplanetary dust particles--grains manufactured in other stars. Some of these stars formed alongside the Sun. Others no longer exist, exploding as supernovae and depositing grains into interstellar space to be included into the mix of material from which the Solar System formed. Pre-solar grains are tiny, less than about 10 micrometers across. They were originally identified in acid-resistant residues when whole chondritic meteorites were dissolved. The residues had extreme isotopic compositions compared to normal Solar System stuff, suggesting an origin outside our Solar System. The ion microprobe has allowed cosmochemists to identify and study grains with anomalous isotopic compositions in place in a sample, greatly expanding our knowledge of these ancient specs. Studies of stardust have joined cosmochemistry with astronomy and astrophysics.

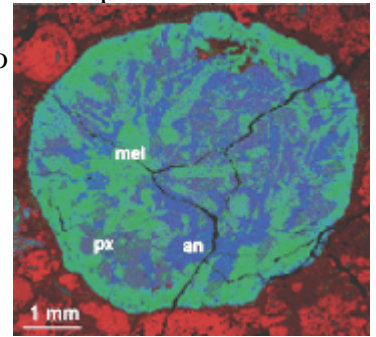


The ion microprobe has also contributed to unraveling the timing of events in the early Solar System. Studies of the decay products of short-lived isotopes (half lives much shorter than the age of the Solar System) have allowed us to distinguish events that took place less than a million years apart, yet over 4.5 billion years ago.

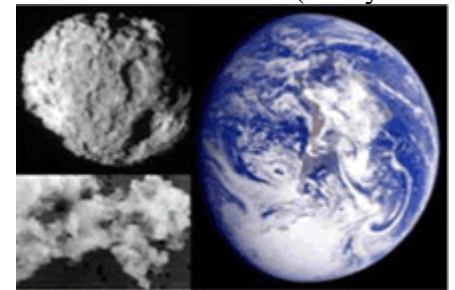
The ion microprobe allows us to date individual chondrules in primitive meteorites, simultaneously measuring other properties. It is all leading to a thorough, if not complete, understanding of what happened when planets were beginning to form around the young Sun. Studies of extinct short-lived isotopes in chondrites will shed light on the stellar sources and timing of their formation compared to the timing of formation of the solar system.



The ion microprobe enhances studies of early solar system processes through measurements of chemical compositions, trace-element abundances, isotopic fractionations, and the unique variations exhibited by oxygen isotopes. Analyses of oxygen isotopes in chondrites and observations of star-forming regions such as the Orion nebula are leading to major leaps forward in our understanding fundamental processes of star and planet formation.



The ion microprobe has also contributed to our understanding of planet formation and initial differentiation (separation into a metallic core surrounded by a rocky mantle and crust). Studies of the ratio of deuterium (heavy hydrogen) to hydrogen in cosmic dust, carbonaceous chondrites, samples returned from the Stardust mission to comet Wild 2, and samples of asteroidal meteorites may allow a definitive determination of the source of water on the Earth. The ion microprobe also contributed mightily to our understanding of the distribution of trace elements in Martian meteorites, helping determine that the mantle of Mars is heterogeneous in composition. Analyses of trace elements such as thorium in tiny volcanic beads collected on the Moon have allowed cosmochemists to improve our estimate of the bulk chemical composition of the Moon, an essential bit of information to understanding the origin of the Moon.



PSRD Articles Featuring the Ion Microprobe

- [Moving Stars and Shifting Sands of Presolar History](#)
- [Using Aluminum-26 as a Clock for Early Solar System Events](#)
- [Silicate Stardust in Meteorites](#)
- [Hafnium, Tungsten, and the Differentiation of the Moon and Mars](#)
- [Gullies and Canyons, Rocks and Experiments: The Mystery of Water on Mars](#)
- [QUE 93148: A Part of the Mantle of Asteroid 4 Vesta?](#)
- [A New Type of Stardust](#)
- [Making Sense of Droplets Inside Droplets](#)
- [From a Cloud of Gas and Dust to an Asteroid with Percolating Hot Water](#)
- [Triggering the Formation of the Solar System](#)
- [Low-temperature Origin of Carbonates Consistent with Life in ALH84001](#)
- [Cosmochemistry from Nanometers to Light-Years](#)

Ion Microprobe Laboratories doing Cosmochemistry and Geochemistry (partial listing, U.S.)

- [SIMS at Laboratory for Space Sciences](#), Washington University in St. Louis, Missouri.
- [SIMS at Hawaii Institute of Geophysics and Planetology](#), University of Hawaii in Honolulu.
- [UCLA National Microprobe Facility](#), Los Angeles, California.
- [Northeast National Ion Microprobe Facility \(NENIMF\)](#), Woods Hole Oceanographic Institution (WHOI), Woods Hole, Massachusetts.
- [GeoSIMS lab at Department of Geological Sciences](#), Arizona State University in Tempe.
- [WiscSIMS lab at the Department of Geology and Geophysics](#), University of Wisconsin-Madison.
- [SIMS facility](#), Sandia National Lab and University of New Mexico, Albuquerque.
- [NanoSIMS lab at Department of Terrestrial Magnetism](#), Carnegie Institution, Washington DC.
- [Stanford University and USGS SHRIMP Lab](#), Stanford, California.

- JSC NanoSIMS, Houston, Texas.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Benninghoven, A., Rüdener, F. G., and Werner, H. W. (1987) *Secondary Ion Mass Spectrometry: Basic Concepts, Instrumental Aspects, Applications, and Trends*, Wiley, New York, 1227 p.
- [Cameca](#) scientific instruments for research.
- [Ion Probe Technique](#) described by the United States Geological Survey.
- Ireland, T. R. (1995) Ion microprobe mass spectrometry: techniques and applications in cosmochemistry, geochemistry, and geochronology. In *Advances in Analytical Geochemistry*, edited by M. Hyman and M. Rowe. JAI Press, Inc., Greenwich, Connecticut, p. 1-118.
- Neal, C. R., Davidson, J. P., and McKeegan, K. D. (1995) [Secondary Ionization Mass Spectrometry \(SIMS\)/Ion Microprobe](#). In [Geochemical analysis of small samples: Micro-analytical techniques for the nineties and beyond](#). U.S. National Report to IUGG, 1991-1994, *Reviews of Geophysics*, Vol. 33 Suppl., © 1995 American Geophysical Union.
- Shimizu, Nobu (2004) If Rocks Could Talk...The ion microprobe extracts hidden clues about our planet's history and evolution. *Oceanus*. <http://www.whoi.edu/oceanus/viewArticle.do?id=2437>
- [SIMS Theory Tutorial](#) from Evans Analytical Group.
- [SIMS Workshop](#).
- [Stardust Mission](#), NASA's comet sample return mission.
- Valley, J.W., Graham, C M., Harte, B., Eiler, J. M., and Kinny, P. D. (1998) Ion Microprobe Analysis of Oxygen, Carbon, and Hydrogen Isotope ratios. In: *Applications of Microanalytical Techniques to Understanding Mineralizing Processes*, McKibben, M.A., Shanks, W.C., III, and Ridley, W.I. (eds.). S.E.G. Review in *Economic Geology*, v. 7, p. 73-97.



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