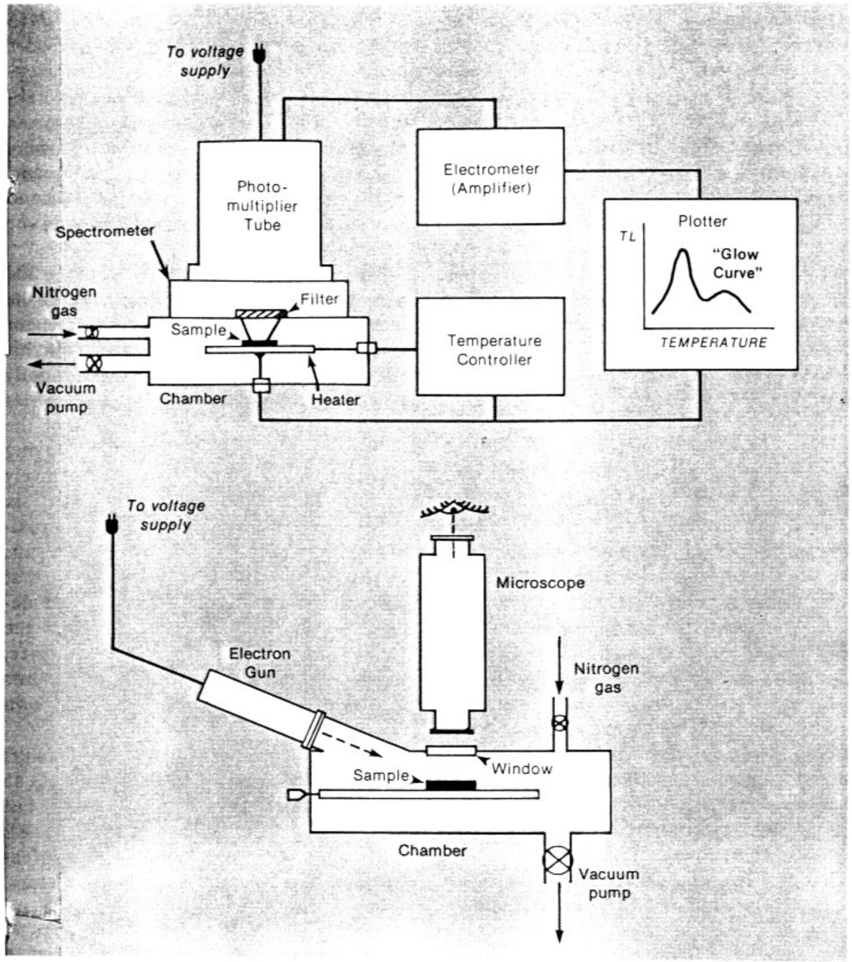


Above: The means for measuring thermoluminescence (top) and cathodoluminescence. Meteorite samples glow when subjected to heat or a beam of electrons in a nitrogen atmosphere, as described in the text.

Below: Alexander Herschel (1836-1907) found that meteorites glow when heated.

Below right: Edward Charles Howard (1774-1816), center, made meteorites glow by applying an electrical discharge. In this Royal Institution picture he is flanked by geologist William Smith (left) and chemist William Allen.

Meteorites That Glow

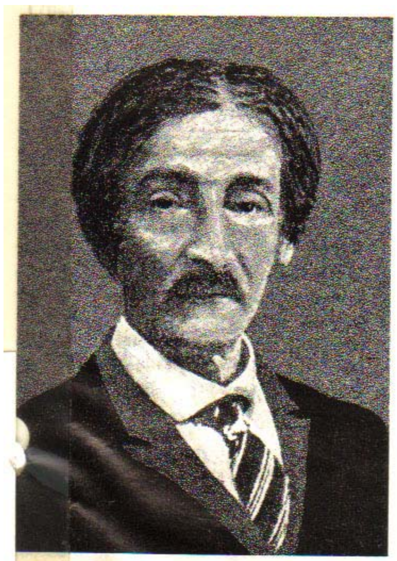
S. W. S. McKEEVER, *University of Birmingham, England* and D. W. SEARS, *University of California, Los Angeles*

METEORITES have a special fascination for students of planetary science. They formed when the solar system began, 4.6 billion years ago, and have been influenced both by the conditions then and by more recent events. No other source can tell us about those events the way meteorites can, if only we can extract the information effectively.

Experimental techniques of meteorite study are many and various, and some have taken a very long time to mature. A prime example is luminescence — the way some meteoritic minerals emit light under certain laboratory conditions.

The first published report of meteorite luminescence appeared in 1802, when Edward Charles Howard observed that a sample of the Benares meteorite glowed in the dark when exposed to an electrical discharge. Some 87 years later, Alexander Herschel (grandson of Sir William Herschel) discovered that some grains from the Middlesbrough meteorite glowed distinctly when sprinkled onto a hot plate in the dark.

Although caused by different processes, the phenomena observed by Howard and Herschel are both evidence of the remarkable ability of meteorite minerals to be luminescent. But only within the last



decade have scientists attempted to capitalize on this property.

MODERN TECHNIQUES

Herschel observed *thermoluminescence* (TL) — a result of heat stimulation. The diagram on the facing page shows a typical layout for the equipment used to study it. A specimen is heated at a controlled rate in a nitrogen atmosphere. It emits light which is picked up by a photomultiplier tube, whose electrical signal is amplified and displayed on a chart recorder. Usually, brightness is automatically plotted as a function of temperature. Alternatively, the wavelengths of the light emitted may be analyzed with a spectrometer.

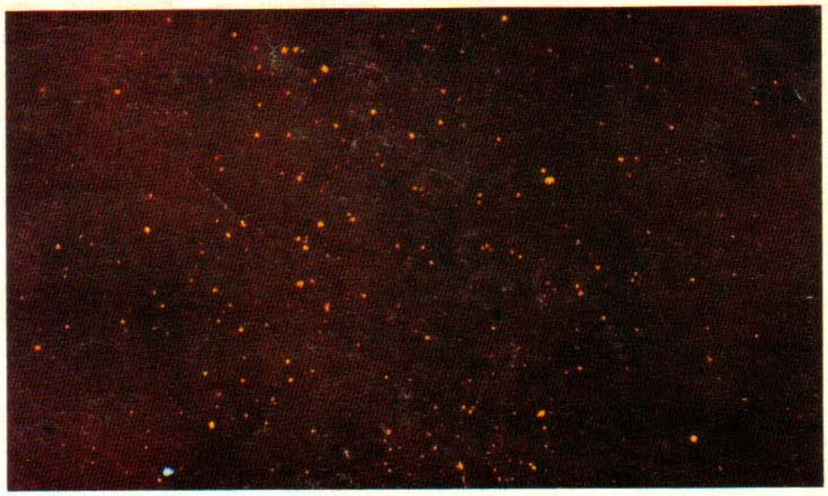
Samples irradiated by an electron beam can glow with what is called *cathodoluminescence* (CL). The electron gun and an optical microscope each point to a spot on the specimen's surface, and the result is observed directly.

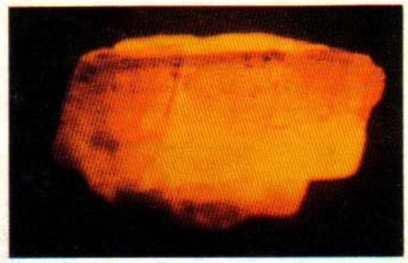
THERMOLUMINESCENCE

A *glow curve* is the graph of TL intensity as it varies with temperature. Two examples are shown on the next page. Ordinary chondrites, the most common meteorites, luminesce brightly with a maximum at about 200° C; a second peak occurs at 350° C, and the color at both peaks is blue-green. Aubrites are a small class of meteorites with an entirely different glow curve, with several peaks and colors ranging from blue to red.

It takes several steps to produce TL. The crystals in meteoroids orbiting in space become energized by ionizing radiation from cosmic rays and, to a lesser degree, from decay of the bodies' own radioactive isotopes of potassium, uranium, and thorium. Some of the energy causes electrons to wander randomly through the solids. Eventually they become trapped at imperfections in the crystal structure. Heating the sample shakes the electrons out of these traps. They then return to their original energy levels; the excess energy converts to photons of visible light.

In ordinary chondrites the mineral feldspar produces the TL; in aubrites, enstatite is primarily responsible.





Thermoluminescence also occurs in terrestrial minerals. At top, grains of calcite and fluorite are sprinkled onto a hot plate. (The effect has been enhanced here by irradiating the grains with gamma rays.) Large crystals of fluorite (at lower left) and calcite glow at different colors at 100° C.

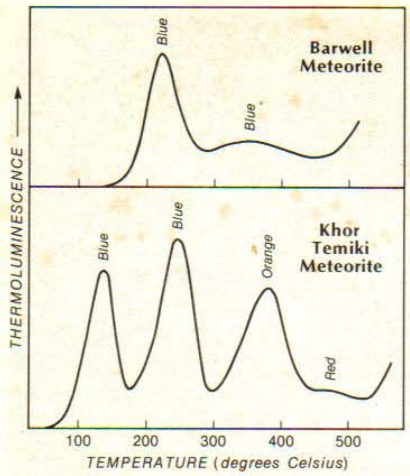
CATHODOLUMINESCENCE

Most thermoluminescent minerals also turn out to be cathodoluminescent. A beam of electrons striking a polished section of the meteorite generates CL that can be seen through a microscope. Basically, the electrons bypass the lattice traps and emit light in a single-step process. CL is bright, so luminescent grains in the slice of meteorite are easy to locate, and they can be photographed through the microscope. This provides a powerful bridge between TL and the many techniques geologists use to examine meteoritic minerals. As in TL, feldspar produces most of the light, a distinctive blue-green.

Feldspar is an important component of ordinary chondrites and the chondrules in them. These chondrules are curious solidified droplets found only in meteorites and some lunar rocks. Their intricate, often beautiful structures are strikingly revealed by CL.

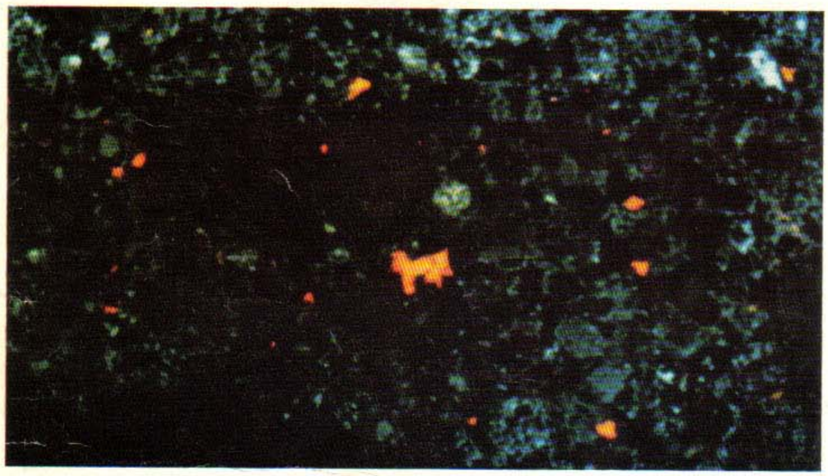
The first scientists who examined chon-

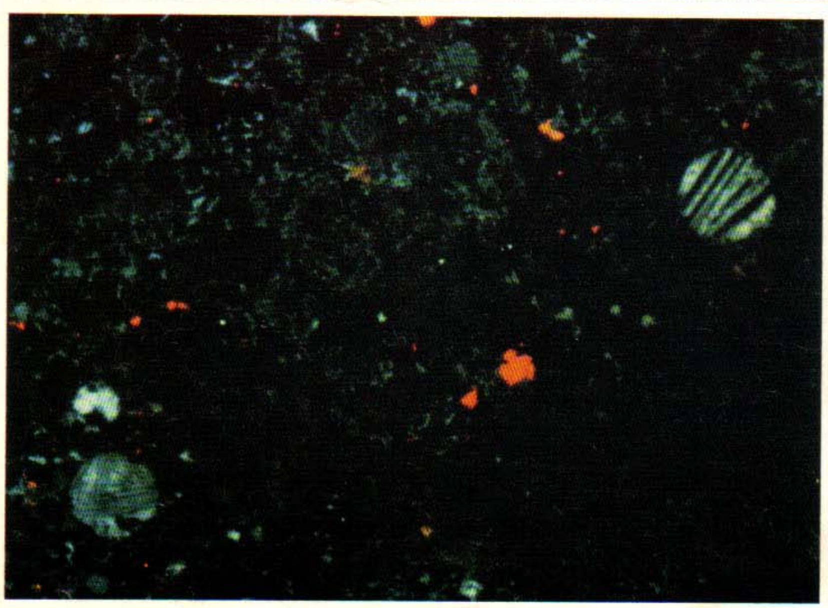
These are two ordinary chondrites. Barwell, right, is a typical pale gray, while the black of McKinney demonstrates that it was severely shocked while out in space. Barwell's red flecks are metallic grains rusting in Earth's moist atmosphere. The ruler is graduated in millimeters.



Above: **Glow curves plot thermoluminescence against temperature. Barwell is an ordinary chondrite, while Khor Temiki is a rarer aubrite.**

Below: **Cathodoluminescence in the Kirin and Dhajala meteorites. The structure of individual chondrules (circular inclusions) is strikingly revealed, especially in the Dhajala sample at bottom. Blue-green and red grains can be seen throughout both samples. The authors supplied all photographs.**





drules microscopically thought they were solidified droplets of "fiery rain" splashed out from the sun. Modern theories are scarcely less spectacular — some think they are solidified droplets of dust which were melted in the primordial nebula by lightning flashes or by meteorite impacts.

APPLICATIONS

A number of small red CL grains have been identified as the minor phosphate mineral chlorapatite. It is important as the host mineral for certain radioactive elements, and once contained the now-extinct isotope plutonium 244. The decay of these elements by nuclear fission releases energetic particles, leaving tracks of damaged material in the crystal, and these may be used to date the meteorite. The difficult task of locating the phosphates is greatly simplified by spotting the red CL against the blue background of feldspar.

Thermoluminescence studies are important to meteorite research in several ways. The amount of TL shown by a meteorite just after falling to Earth is governed by its exposure to high-energy radiation and by the temperatures it experienced in space. These act in opposite senses — radiation increases TL, heat lowers it. In most meteorites the TL level has settled to a uniform level, but we have discovered several in which it is lower than expected. They act as if they had been heated prior to our laboratory studies.

The fiery heat of the plunge through the atmosphere does not penetrate the meteorite more than four or five millimeters, so that it cannot effect the TL at greater depths. They may have been heated some other way — perhaps by passing close to the sun. TL provides a promising means of recognizing these meteorites.

On reaching Earth, meteorites are protected from the high-radiation environment of space and the TL subsides to a new, much lower level. Theoretically, this decrease in TL provides a means to estimate how long ago a meteorite fell. This idea has been tested by examining a great many meteorites, some of which fell recently and some many thousands of years ago. The results are consistent with computer predictions of how TL drops with time. This, in turn, helps in estimating the terrestrial lifetimes of meteorites in the two parts of the world where finds are most common — the American Prairies and Antarctica. In the United States, it seems, meteorites can lie undiscovered on the ground for up to 20,000 years; in Antarctica, most samples are at least 10,000 years old.

Some meteorites not only have low TL when examined, but seem incapable of displaying much even when artificially irradiated in a laboratory. These samples are usually black or almost white instead of the usual pale gray, and they also have very low radiometric ages. Chondrites typically were formed about 4.6 billion years ago, but the black ones seem to be a mere half-billion years old. Therefore, about that time some meteorites suffered a violent event which caused them to blacken and lose their TL and CL. Laboratory experiments have demonstrated that these effects can result from intense shock. The event suffered by the black chondrites is commonly believed to be the shock and heating attending the breakup of the parent body of those meteorites.

These studies are barely a beginning. The luminescence of meteorites may not be a new discovery, but we believe it offers many possibilities for new ways to study these enigmatic bodies from space.