

X-Ray Observations of Young Stars Address a Puzzle of the Solar System's Origin

Since its launch in July 1999, NASA's Chandra X-Ray Observatory has been orbiting Earth in a highly eccentric 2.3-day orbit. At a recent celebratory conference in Washington, DC, entitled "Two Years of Chandra Science," x-ray astronomers reported an impressive variety of findings made possible by Chandra's extraordinary imaging and spectroscopic capabilities. (See PHYSICS TODAY, November 2000, page 19.)

One of the new findings announced at the conference addresses a long-standing puzzle about the origin of our Solar System. Eric Feigelson (Pennsylvania State University) reported on the observation, by his Penn State-Caltech collaboration, of surprisingly vigorous x-ray flaring from a selection of 41 very young stars in the Orion Nebula Cluster. The ONC, spawned in a large nursery of molecular gas and dust, is the richest dense accumulation of young stars in our corner of the Galaxy.

The 41 young stars scrutinized by Feigelson and company were selected because their masses were close to that of the Sun. The history of a star depends primarily on its mass. Ranging in age from about 10^5 to 10^7 years, these 41 stars are meant to serve as observational surrogates for the turbulent infancy of the Solar System, which is now a mature, sedate 4.6-billion years old.

The isotope problem

The primary conundrum on which these surrogates for the young Sun are intended to shed light is the surprising presence of telltale daughters of certain short-lived isotopes in small, once-molten pebbles embedded in a class of meteorites that are thought to be pristine representatives of the material comprising the disk of dust and rock that orbited the embryonic Sun. For example, embedded pebbles rich in calcium and aluminum show decay products of the rare, short-lived isotopes ^{41}Ca , ^{26}Al , ^{10}Be , and ^{53}Mn .

All the isotopes in question have lifetimes of a few million years or less. Thus

Must we really invoke a supernova midwife to explain why the newborn Solar System harbored so much short-lived radioactivity? Maybe not.

their presence in primordial disk material poses a perplexing problem of timing: Having been melted into pebbles together with their stable chemical kin from dust balls in the circumstellar disk, the short-lived isotopes could not have existed much before the disk was formed. And yet, none of these elements could have been made by nucleosynthesis in a young star as light as the Sun. The stable isotopes, by contrast, had no such time constraints. They were spewed into the interstellar space by supernovae over long eons. Explaining where the problematic short-lived isotopic species—some 10 of them in all—were created has been a major challenge to theories of the Solar System's origin.

Until now, the favored explanation

for the isotopic anomalies has been a scenario first put forward by Alastair Cameron at Harvard in 1977. He suggested that, 4.6 billion years ago, a massive type-II "core-collapse" supernova exploded very close to the cloud of molecular gas and dust that was to become the Solar System. Such a nearby cataclysm, Cameron pointed out, would have performed a double function: It would have shocked the cloud into beginning the contraction that produced the Sun and its orbiting disk, and it would have seeded the cloud with short-lived isotopes created in the supernova.

A troubling aspect of this *deus ex machina* scenario is that it makes our Solar System something of a special case. In the whole Galaxy, there are only a handful of type-II explosions per century—probably not enough to play midwife to the many stars that are constantly being born. But type-II supernovae are only found in star-forming regions. And over a few million years, a supernova remnant can

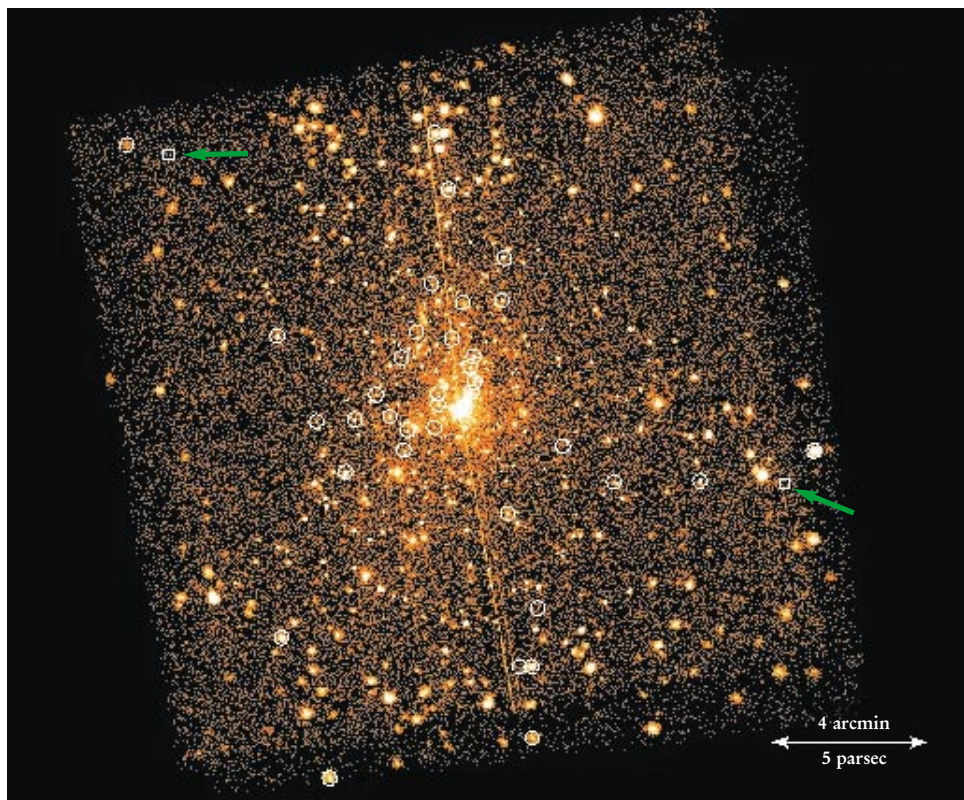


FIGURE 1. X-RAY IMAGE OF THE ORION NEBULAR CLUSTER of young stars, recorded by Chandra X-Ray Observatory's ACIS imaging spectrometer in two 12-hour exposures. Of the nearly 1100 sources discerned in the image, more than 90% were identified with optically known stars. Of the 41 stars with masses close to that of the Sun, 39 (shown circled) produced x-ray images. The boxes (with green arrows) show the positions of the only two solar-mass stars that revealed no discernable x-ray emission.

indeed seed a nonnegligible fraction of the Galaxy with radioisotopes. However, Feigelson argues, ^{41}Ca , the shortest-lived of problematic isotopes, is particularly hard to account for. With a half-life of only 10^5 years, its presence when the meteoric pebbles were being formed would require fine tuning in a supernova scenario.

Maybe it's spallation

There is an alternative. Almost all the short-lived species can be produced by spallation—that is, MeV protons and light ions knocking pieces off stable nuclei. Such energetic particles are known to be produced nowadays by the Sun in occasional magnetic flares of unusual violence, caused by the reconnection of field lines above the solar surface. (See last month's *PHYSICS TODAY*, page 16, for a discussion of reconnection on a smaller scale in Earth's magnetosphere.) The plasma heated by these magnetic events manifests itself as x-ray flares. That's what Feigelson and company were looking for in the Chandra observations of young solar-mass stars in the ONC.

In the present-day Sun, such violent magnetic reconnection flares are much too infrequent, and their energetic-particle fluxes much too small, to account for the abundance of short-lived isotopes that ended up in the pebbles. Nor are cosmic-ray fluxes sufficient to do the spallation trick. For some time, however, there's been considerable qualitative evidence that much younger sunlike stars do a lot more magnetic flaring than the mature Sun. But is it enough to account for the isotopic anomalies?

ROSAT, the German x-ray satellite launched in 1990, was able to study a few solar surrogates in clusters of young stars closer than the ONC. But the much richer Orion cluster was too distant (1500 light-years) and crowded for the limited angular resolution and sensitivity of ROSAT to let the observers pair up individual x-ray sources with the stellar optical data necessary for estimating the masses and ages of specific stars.

To examine in quantitative detail the magnetic flaring activity of young solar-mass stars as a function of age, the Penn State–Caltech group availed itself of the ONC—the only known cluster that could provide a large, unbiased sample of such immature stars. Chandra's superb x-ray mirrors provided the arcsecond resolution needed to identify individual stellar x-ray sources with their optical counterparts. And the ACIS imaging spectrometer array in its focal plane

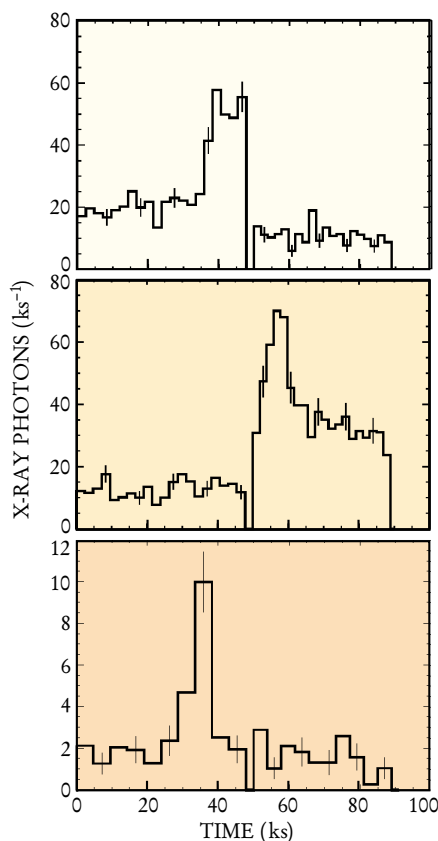


FIGURE 2. TIME PROFILES of the x-ray output of three typical young solar-mass stars in the Orion cluster show almost daily outbursts of prominent flaring. The breaks near 50 ks separate the Chandra observation into the two 12-hour exposures taken 6 months apart.

provided the requisite high quantum efficiency for recording x-ray photons with very little noise.¹ ACIS was developed at Penn State and MIT under the leadership of Gordon Garmire.

The richest field

The Penn State–Caltech group exposed the CCD array of the imaging spectrometer to the Orion cluster for two 12-hour periods six months apart. (It's the large eccentricity of Chandra's orbit that makes uninterrupted 12-hour exposures possible.) The resulting image, shown in figure 1 integrated over photon energies from 0.5 to 8 keV, is described by Feigelson as “the richest single field of sources ever obtained in the history of x-ray astronomy.” With a lower detection limit of 7 x-ray photons per source, the group found almost 1100 stellar x-ray sources in this one field.

The group was able to identify more than 90% of these 1100 sources

with specific stars listed in recent optical and infrared catalogs of the Orion cluster. A star's location on the Hertzsprung–Russell diagram of luminosity versus temperature, as deduced from the optical and infrared data, essentially determines its mass and stage of development. Of the thousands of known Orion cluster stars located in the field of figure 1, the optical catalogs list only 41 whose temperature and luminosity imply a mass between 0.7 and 1.4 times the Sun's mass. Amazingly, all but two of these young solar surrogates correspond to x-ray sources detected by Feigelson and company.

These 39 sources are marked in the figure by circles. The locations of the only two solar-mass stars for which no x-ray emission was detected during either of the 12-hour exposures are indicated by squares. All of these 41 young solar-mass stars are still in the so-called pre-main-sequence T Tauri phase, in which nuclear fusion has not yet become the principal energy source.

The typical time variability of the solar surrogates' x-ray output (see examples in figure 2) indicates that prominent magnetic flaring outbursts lasting several hours are an almost daily occurrence in these young stars. In the mature Sun, by contrast, the interval between powerful magnetic-reconnection flares is measured in months or years.

Averaged over the 41 young solar-mass stars, the x-ray flares are about 100 times more luminous than the most powerful solar flares we see from the Sun, and they are almost 100 times more frequent. Even the “quiescent” x-ray output between flares is a thousand times more intense than the quiescent x-ray output of the mature Sun. Adding to this the non-linear scaling of MeV proton output with x-ray luminosity, the Penn State–Caltech group estimates that the young Sun, in its T Tauri phase, spewed out particles energetic enough to cause spallation at a rate that exceeds its current flux by 5 or 6 orders of magnitude. Furthermore, strong electromagnetic radiation from those early flares may have been responsible for the melting that turned dust balls from the disk into metallic pebbles.²

“Our observation of ubiquitous x-ray flaring does not, by itself, establish that the short-lived isotopes were in fact produced in the disk by protons and ions accelerated in the solar flares,” Feigelson told us. “But it provides a quantitative basis for the spal-

lation calculations³ of the nuclear astrophysicists.”

Cameron, for one, is skeptical.⁴ Spallation, he agrees, might account for neutron-short isotopes like ²⁶Al. But he doubts that it could have produced the anomalous meteoritic populations of neutron-rich isotopes like iron-60. He also points out that the flux of energetic protons, and therefore the spallation rates, should have decreased with distance from the accelerating flares. “That picture,” he told us, “is contradicted by the striking uniformity of the isotope anomaly from one meteorite to another.” Cameron remains unconvinced by a protosolar-wind mechanism, proposed by Frank Shu and coworkers at the University of California, Berkeley, that might account for this uniformity.²

“The problem,” says Feigelson, “is that we don’t really know where, in the protosolar star-disk system, the flares we see are actually occurring.” It’s not yet clear whether, as in the mature Sun, the flaring magnetic structures are entirely rooted in the young star’s surface. Magnetic interaction with the circumstellar disk may turn out to be important. As continuing contraction tends to increase the young star’s spin, magnetic coupling to the disk might be serving as a brake. There’s also the question of the character of the internal dynamo that generates a solar-mass star’s magnetic field during its T Tauri phase. It might be quite different from the dynamo operating in the mature Sun. The Penn State-Caltech group hopes to report on these important astrophysical issues in the near future.

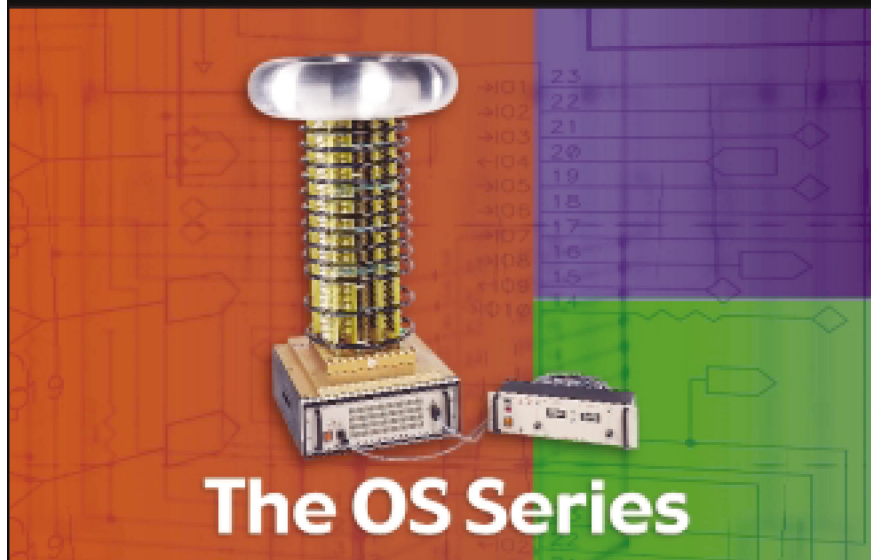
Donald Clayton (Clemson University) suggests that natural history might not be as tidy as we would wish. “Now that the Orion cluster observations have shown how very active all young solar-mass stars are, we no longer have to pull a supernova rabbit out of a hat to account for all the short-lived isotopes,” he told us. “But to account for the ⁶⁰Fe, we might still have to invoke a supernova in addition to energetic spallation particles from magnetic reconnection flares.”

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