ASTRONOMY

The Cradle of the Solar System

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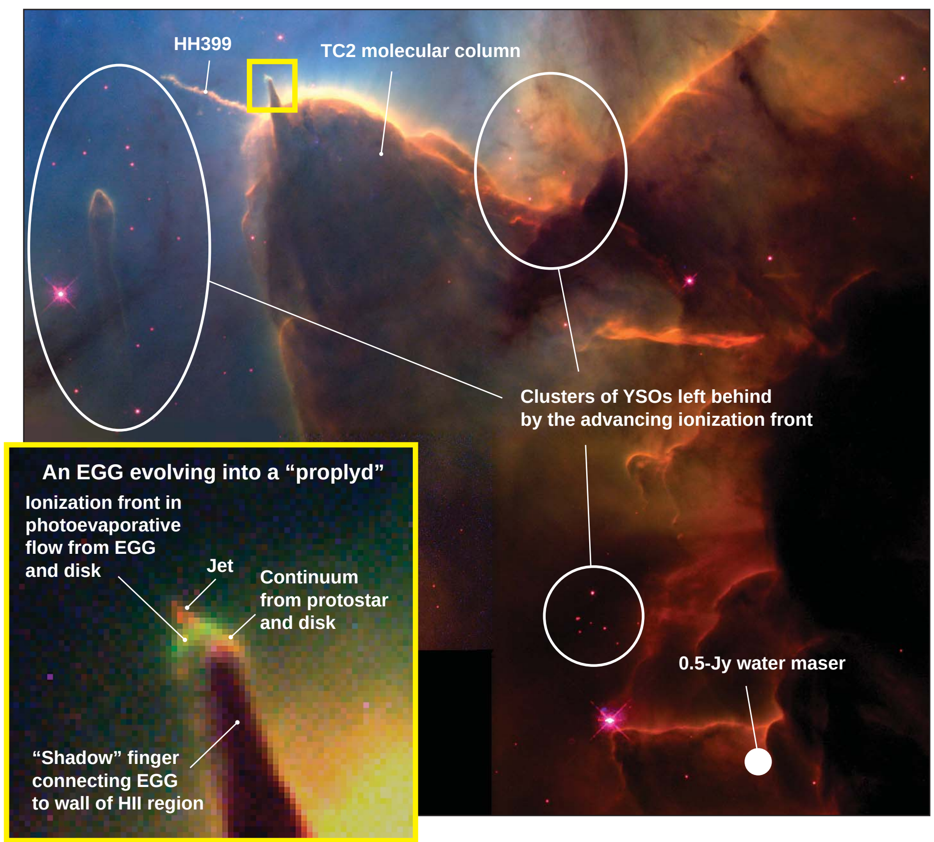
What kind of environment gave birth to the Sun and planets? Most astronomers who study star formation would probably say that the solar system originated in a region much like the well-studied Taurus-Auriga molecular cloud (*1*)—a region in which low-mass, Sun-like stars form in relative isolation—but this conventional wisdom is almost certainly incorrect. Recent studies of meteorites confirm the presence of live ^{60}Fe in the early solar system (*2*). No known mechanism could have formed this short-lived (half-life = 1.5 million years) radionuclide locally within the young solar system. However, ^{60}Fe is produced in supernova explosions, along with ^{26}Al, ^{41}Ca, and other radioisotopes (*3*). Material from nearby supernovae must have rapidly mixed with the material from which the meteorites formed. The implications of this are clear. The Sun did not form in a region like Taurus-Auriga. Rather, like most low-mass stars (*4*), the Sun formed in a high-mass star–forming region where one or more stars went supernova. Understanding our origins *means* understanding the process of low-mass star formation in environments that are shaped by the presence of massive stars.

The intense ultraviolet (UV) radiation from massive stars carves out ionized cavities and blisters in the dense molecular clouds within which the stars formed. Examples of these regions of ionized gas, called HII regions, include such well-known objects as the Orion Nebula and the Eagle Nebula. There is growing evidence that most low-mass star formation in such environments is triggered by shocks driven in advance of the HII region ionization front as it expands into its dense surroundings (*5*). Stars seen in the ionized volumes of HII regions were formed in this way, and then subsequently were uncovered by the advance of the ionization front itself.

Low-mass stars that form around an HII region should pass through a well-defined sequence: (i) A shock driven in advance of an ionization front compresses molecular gas around the periphery of an HII region, compressing dense cores and causing them to become unstable to gravitational collapse (*6*). (ii) These cores are overrun by the advancing ionization front within ~10^5 years. As cores emerge into the HII region interior, they go through a short-lived (~10^4 year) phase during which the dense core itself photoevaporates. This is the "evaporating gaseous globule" or EGG phase best seen in Hubble Space Telescope (HST) images of the Eagle Nebula (*7*). (iii) EGGs that do not contain stars are dispersed, but when a star-bearing EGG evaporates, the circumstellar disk inside is exposed directly to UV radiation from the massive stars. The object transitions into an "evaporating disk" phase, best seen in HST images of "proplyds" in the Orion Nebula (*8*). (iv) The evaporating disk phase is also short-lived (*9*). Within a few tens of thousands of years, photoevaporation erodes the gaseous disk to within a few tens of astronomical units of the central young stellar object (YSO) (*10*). (v) The young star and its truncated disk then reside within the ionized, low-density interior of the HII region for the remainder of the few-million-year lifetime of the region. This is the environment in which planetary systems such as our own form. (vi) When the massive stars exciting the region go through a high mass-loss "Wolf-Rayet" phase and/or go supernova, the protoplanetary disks surrounding nearby low-mass YSOs are pelted with ejecta. Such events are responsible for the short-lived radionuclides found in meteorites in our own solar system.



Planetary system nursery. Hubble Space Telescope wide-field camera observation of a field in the southern portion of the Trifid Nebula illustrating several of the observational consequences of the star-formation scenario discussed. The inset (an enlargement of the region indicated by the small yellow box) shows a YSO-bearing EGG seen as it is evolving into a "proplyd." Evidence for triggered star formation in the region includes the HH399 jet, which arises from an embedded source immediately interior to the ionization front, and the presence of a 0.5-Jy water maser. Clustering of YSOs, especially around the remains of a largely evaporated column in the upper left of the field, is evidence of pockets of triggered star formation that have been overrun by the ionization front.

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This scenario for star formation makes many testable predictions that are supported by observations already in the literature. For example, fingerprints of the star-formation process discussed here are clear in the HST image of a region in the Trifid Nebula (*11*) shown in the figure. In this region, intense UV radiation from a massive star (located well above the field of view) is incident on the surface of dense molecular gas that fills most of the field of view. Sharply defined orange and yellow features mark the current location of the ionization front. The HH399 jet originates from an unseen protostar located a short distance from the ionization front. A water maser is also seen in projection a short distance behind an ionization front. Jet and maser activity are both evidence of continuing accretion onto these two very young protostars. In 10,000 years or so, both of these objects will be cut off from their accretion reservoirs when they are overrun by the advancing ionization front. When this happens, these objects will be seen as EGGs, much like the prominent EGG shown in the inset.

The EGG seen in the figure is itself a remarkable demonstration of the evolutionary tie between EGGs and proplyds. From the bottom down, this feature is a classical EGG, of the sort seen in the Eagle Nebula. But at the tip of this EGG we see a star, a small reflection nebula, a small protostellar jet, and an ionization front in the evaporative flow off the tip of the structure. These features are all characteristic of the proplyds seen in the Orion Nebula (*8*). In other words, this object is undergoing the transition from EGG to proplyd.

One of the clearest predictions of this scenario is that star formation is a sequential process. There should be a clear relationship between the properties of YSOs and their distance from the ionization front. Many lines of evidence confirm this prediction. For example, Hα-bright protostars are known to be concentrated near ionization fronts in numerous HII regions (*12*), as are water masers and other tracers of star formation (*5*). The sequential nature of star formation is also apparent in the figure, where the protostars within the ionized volume of the HII region are clustered into several small groups that were left behind by the advance of the ionization front. One such group in the upper left portion of the field is especially telling, because these stars still surround a small molecular teardrop—the remnant of the larger molecular core that gave birth to these stars and was subsequently evaporated by the advance of the ionization front. This is what the adjacent TC2 molecular column will look like in ~100,000 years.

Most low-mass stars and planetary systems, including our own, formed in HII region environments. A unified description of this orderly process has broad implications. For example, the initial distribution of stellar mass is largely a consequence of this process. Closer to home, the solar system formed from a truncated disk bathed in intense UV radiation from massive stars and subjected to the effects of nearby supernovae. This scenario has consequences for questions as diverse as the truncated outer edge of the Kuiper Belt, oxygen-isotope anomalies in meteorites, and the differentiation of planetesimals driven by decay of short-lived radionuclides. The fields of astrophysics, meteoritics, astrobiology, and planetary science meet in the early solar system. The setting for that encounter is not the dark interior of an isolated molecular cloud, but rather the far more violent environment around the periphery of an HII region. The predictive scenario for the origin of low-mass stars proposed here, with its roots in the study of both meteorites and star formation, provides a context and direction for future work in each of these fields, and in the theory that unites them.

References

1. F. C. Adams, G. Laughlin, *Icarus* **150**, 151 (2001).
2. S. Tachibana, G. R. Huss, *Astrophys. J.* **588**, L41 (2003).
3. B. S. Meyer, D. D. Clayton, *Space Sci. Rev.* **92**, 133 (2000).
4. C. L. Lada, E. A. Lada, *Annu. Rev. Astron. Astrophys.* **41**, 57 (2003).
5. K. R. Healy, J. J. Hester, M. J. Claussen, *Astrophys. J.*, in press.
6. F. Bertoldi, C. F. McKee, *Astrophys. J.* **354**, 529 (1990).
7. J. J. Hester *et al.*, *Astron. J.* **111**, 2349 (1996).
8. J. Bally, C. R. O'Dell, M. J. McCaughrean, *Astron. J.* **119**, 2919 (2000).
9. J. Bally *et al.*, *Astron. J.* **116**, 854 (1998).
10. D. Johnstone, D. Hollenbach, J. Bally, *Astrophys. J.* **499**, 758 (1998).
11. J. J. Hester *et al.*, *Bull. Am. Astron. Soc.* **31**, 932 (1999).
12. K. Sugitani *et al.*, *Astrophys. J.* **565**, L25 (2002).

EVOLUTION

Insights into Innovation

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In his *Theory of Economic Development* (*1*), the economist Joseph Schumpeter distinguished between inventions—the creation and establishment of something new—and innovations, inventions that become economically successful and earn profits. In this distinction, Schumpeter echoes an earlier dichotomy in biology between the physical sources of genetic and phenotypic variability among organisms and those factors leading to the establishment (fixation) of a favored variant within a population. Schumpeter's definition of invention intentionally includes fixation, and thereby highlights the elusive nature of innovation with its connotation of influence and success.

The theoretical foundations of evolutionary invention and innovation were discussed at a recent workshop at the Santa Fe Institute (*2*). The meeting brought together biologists, paleontologists, technologists, and economists to consider the nature of evolutionary novelty and the similarities and differences between biological and technological invention and innovation.

Case studies of invention and innovation abound, from the Cambrian radiation of animals in biology to the telegraph, telephone, and Internet in technology, and some are sufficiently beguiling to obscure an evident lack of generality. Three explanations for the absence of robust, general theories of invention and innovation emerged at the meeting. First, "innovation" and "novelty" are two of the most overused and misunderstood words in evolutionary biology. For example, some meeting participants defined novelty as rare morphological transitions that result from breaching genetic or morphological constraints, exemplified by a developmental mutation in the Yucca moth that gave rise to a new antennal limb (*3*). Others defined novelty as changes that have important consequences for the environment, the classic example being the origin of oxygen-dependent photosynthesis that led to an oxygenated atmosphere. Still others defined novelty as changes resulting in the generation of abundant taxonomic diversity, such as the cichlid fishes of East African lakes or the diversification of flowering plants. Second, scale is a problem: morphological innovations in the fruit fly *Drosophila* challenge developmental biologists studying mutations in homeobox genes that affect embryonic development (Nipam Patel, University of California, Berkeley). Yet mutations in homeobox genes and associated morphological changes may be dismissed as unimportant by paleobiologists interested in larger scale changes. Finally, many discussions ignore

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