Young Stars Near Earth: Progress and Prospects
ASP Conference Series, Vol. 244, 2001
Ray Jayawardhana and Thomas P. Greene, eds.

Observations of Nearby Young Solar Analogs

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Abstract. Studies of young, solar-mass stars provide information about the astrophysical conditions experienced by any young planetary systems around these objects. The primitive Earth may have been subject to a similar environment that affected its evolution and the origin of life on its surface. A robust description of the statistics of plausible environments and their relationship to early Earth history require observations of a well-defined, unbiased sample of young solar analogs. We have constructed a volume-limited ($d < 25$ pc) catalog of $\sim$50 single, solar-type stars with estimated ages less than 800 milion years, corresponding to the Hadean epoch on Earth. Candidate stars were initially selected based on their zero-age main-sequence position in the HR diagram and high coronal X-ray luminosities. Spectroscopic/close binary systems were eliminated and high stellar activity, rapid rotation rate, and high lithium abundance have been subsequently confirmed by follow-up spectroscopy and photometry of most stars. Completed or ongoing observations include those at radio wavelengths to place upper limits on mass loss, in the thermal infrared to detect warm circumstellar dust, at near infrared wavelengths to search for low-mass companions, in the near- to far-UV to measure radiation relevant to photochemistry in planetary atmospheres, and of extreme UV responsible for heating upper atmospheres and the escape of hydrogen and loss of water from planets.

1. Introduction

Our knowledge of the first 800 million years of Earth history (the Hadean epoch) is extremely limited, but the available record suggests that it included profound events such as the Moon-forming impact, the removal of a primordial atmosphere, the advent of plate tectonics, the appearance of oceans, and possibly, the origin of life. Conditions on modern Earth are influenced by its astrophysical environment (radiation, solar wind, impacts) and this was probably much more so during the Hadean. Stellar evolution models predict a solar luminosity 70-75% of the modern value which, all else being equal, would allow mean surface temperatures on Earth to fall below freezing. Chromospheric emission at ultraviolet and coronal emission at X-ray wavelengths was more intense, a consequence of rapid rotation and enhanced magnetodynamo activity. Ultraviolet emission was involved in the photochemistry of atmospheric greenhouse gases and any prebiotic organic compounds. Extreme ultraviolet emission, Lyman α, is heats the Earth's thermosphere and sustains the escape of hydrogen. Higher Hadean EUV fluxes could have driven the massive escape of hydrogen, both primordial and that from photodissociated water. The lunar surface records a period of intense bombardment during this epoch and well after the end of planetary accretion. On the Earth, this bombardment may have driven atmospheric escape, imported volatiles, and even delayed the origin of life. Studies of young Sun-like stars are a means of describing possible conditions in the early Solar System during this early epoch. However, previous studies have been hampered by the lack of a well-defined sample. The advent of all-sky surveys have made the identification of such a sample possible. We have constructed a catalog of nearby young solar analogs and are carrying out a multi-wavelength campaign using both space- and ground-based instruments to characterize these stars and their circumstellar environments.

2. Selection of Nearby Young Solar Analogs

Candidate young stars can be identified by their location on the zero-age main sequence (ZAMS) in the Hertzsprung-Russell (HR) diagram and their luminous X-ray coronae (Fig. 1). The *Hipparcos* catalog of stellar positions, parallaxes, proper motions, and photometry was correlated with the all-sky Bright Source Catalog of X-ray sources detected by the *Roentgen* X-ray satellite (ROSAT). The selection criteria were (1) $d < 25$ pc; (2) location on or near the ZAMS based on absolute magnitude M_V and $B-V$ color; (3) $L_x/L_{bol} > 1.4 \times 10^{-5}$; (4) M_V within a narrow range centered on the expected value of the Sun at 4.2 Ga and corresponding to spectral types G0-K2 (the early Sun was a G5 star); and (5) absence of stellar companions within a projected distance of 800 AU (Gaidos 1998). Follow up spectroscopy and photometry (Gaidos, Henry & Henry 2000) was used to eliminate spectroscopic binaries and measure other indicators of stellar age, including rotational broadening of stellar lines, emission in the H and K lines of Ca II, the abundance of Li, and rapid rotation (Fig. 2).

The first catalog of nearby young solar analogs was X-ray flux limited: The flux limit for a complete 25-pc volume-limited sample is 3.1×10^{-13} ergs s^{-1} cm^{-2} while the the 92% completeness limit of the *Rosat* Bright Source

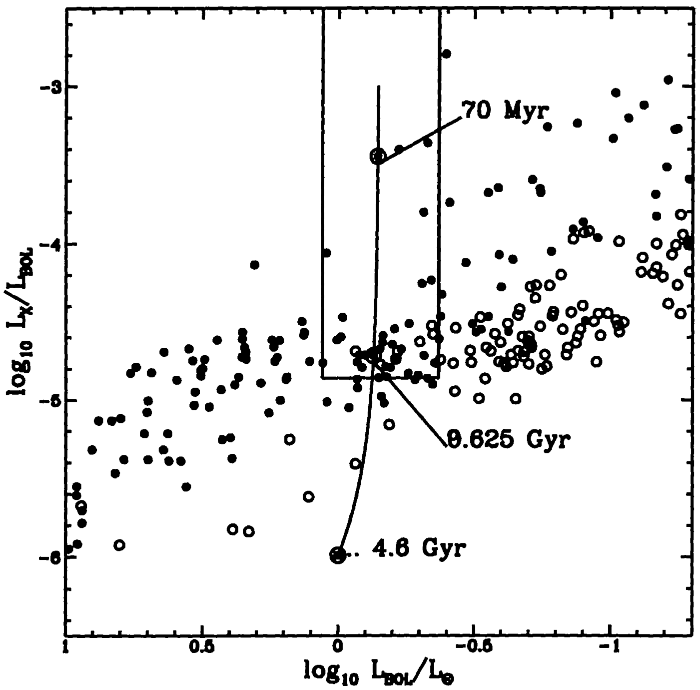

Figure 1. The predicted trajectory of the Sun from 32 Myr to the present in a plot of specific *Rosat*-measured X-ray luminosity R_X versus bolometric luminosity. Ages of 70 and 625 Myr correspond to those of the Pleiades and Hyades clusters. Hyades detections (filled points) and upper limits (open points) from Stern et al. (1995) are plotted. The selection box for young solar analogs whose lower boundary corresponds to the predicted solar value of R_X at an age of 0.8 Gyr is shown. From Gaidos (1998).

Catalog is only 6×10^{-13} ergs s^{-1} cm^{-2}. However, the recently released, deeper Faint Source Catalog permits the construction of a true volume-limited sample. Additional candidate stars have been selected on space-motion rather than X-ray flux: The entire *Hipparcos* catalog, which is complete for all G stars to 25 pc, has been searched for stars who may be co-moving, and austensibly co-eval, with known young solar analogs. The possible space motions of a star whose (*Hipparcos*) proper motion, but not radial velocity, is known describe a line in velocity space. If the line passes close to the motion of a known young star it is possibly co-moving and is further investigated. This generates a managable number of candidates whose radial velocity can be obtained from the literature or measured.

3. Recent Observations and Discoveries

The photospheric abundance of some of the major elements (Fe, Si, Mg, Ca, Ti, etc.) have been derived from high-resolution echelle spectroscopy of the young solar analogs. Data on the heavy-element abundances are important for interpreting spectra of chromospheric emission lines. Solar-mass stars that originated

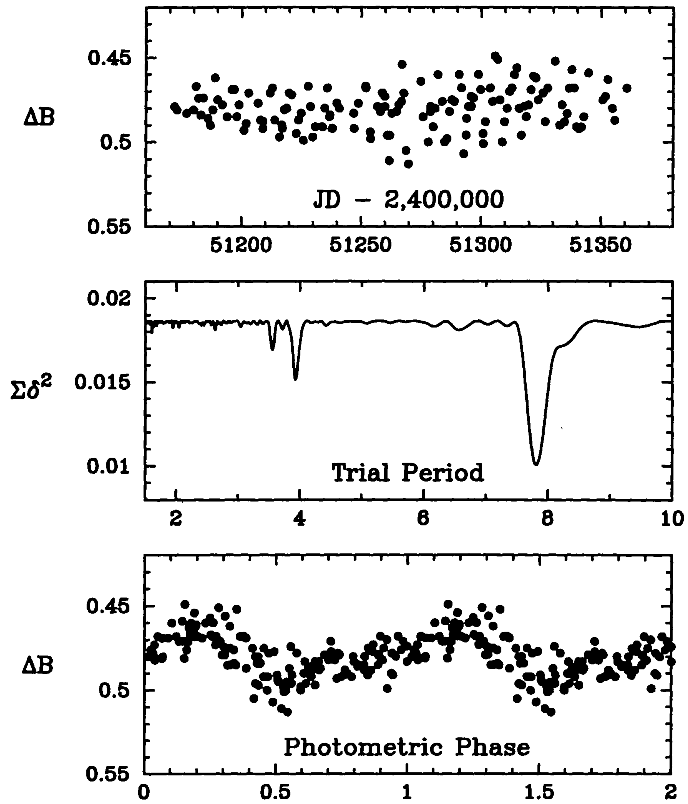

Figure 2. *Top:* Johnson *B* photometric observations of HD 116956 acquired with the T3 0.40 m automatic photoelectric telescope at Fairborn Observatoryplotted against Julian Date. *Middle:* Periodogram of the observations. The sum of the squares of the residuals from a least-squares sine fit are plotted against trial period in days. The resulting period is 7.81 ± 0.02 days. *Bottom:* The photometric observations from the top panel plotted against photometric phase computed with the 7.81-day period and an arbitrary epoch.

from the same molecular cloud may have similar chemical compositions and thus young solar analogs that are kinematically related may also share certain abundance patterns. Fig. 3 is a plot of [Si] vs. [Fe] relative to solar. Although there is significant variation in [Fe] among kinematically similar stars, the stars with low Si relative to Fe that form a lower line in this diagram have similar space motions. The deepest radio observation of a main sequence star (π^{01} UMa) other than the Sun was obtained by the VLA and set upper limits on mass loss rate through a stellar wind (Gaidos, Guedel & Blake 2000). Observations of several young solar analogs were recently completed by the instruments on the Extreme Ultraviolet Explorer (EUVE) satellite to construct a plausible EUV spectrum of a young solar-type star. A single flare observed during one of the observations of HD 43162 is notable for its large energy and extremely cool emission spectrum.

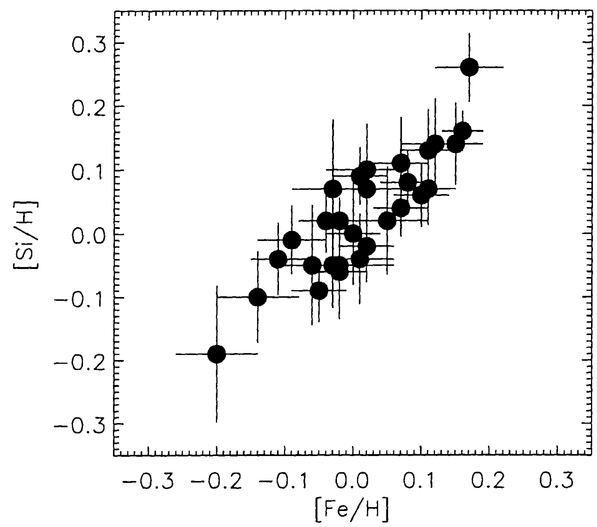

Figure 3. Si abundance vs. Fe abundance (relative to solar) for young solar analog stars. The stars lying on a line with low [Si/Fe] have similar space motions.

4. Future Observations

Observations by the recently launched Far Ultraviolet Spectroscopic Explorer (FUSE) will bridge an important range of UV wavelengths between those detectable by HST-STIS and EUVE. The achievement of beam combination in the Keck Interferometer heralds opportunities to resolve the AU-scale dust environment of nearby stars in the thermal infrared: The 10-micron resolution of the 85-meter baseline corresponds to a linear scale of 0.5 AU at a star 20 pc away and in "nulling" mode the interferometer will be optimized for detection of dust at 0.3-1 AU distances from such a star, a spatial scale similar to that of the peak emission from the Solar System's zodiacal cloud. The nearby young solar analogs, which may have significant circumstellar dust, are very appropriate targets for initial KI investigations. The Space Infrared Telescope Facility (SIRTF), schedule for launch in 2002, will offer unprecedented sensitivity and spectroscopic capability to characterize any dust around these stars. Finally the detection of a giant planet around the young solar analog HD 1237 (Naef et al. 2000) means that future space-based interferometers can study not only the environments of nearby young systems, but the resident planets themselves.

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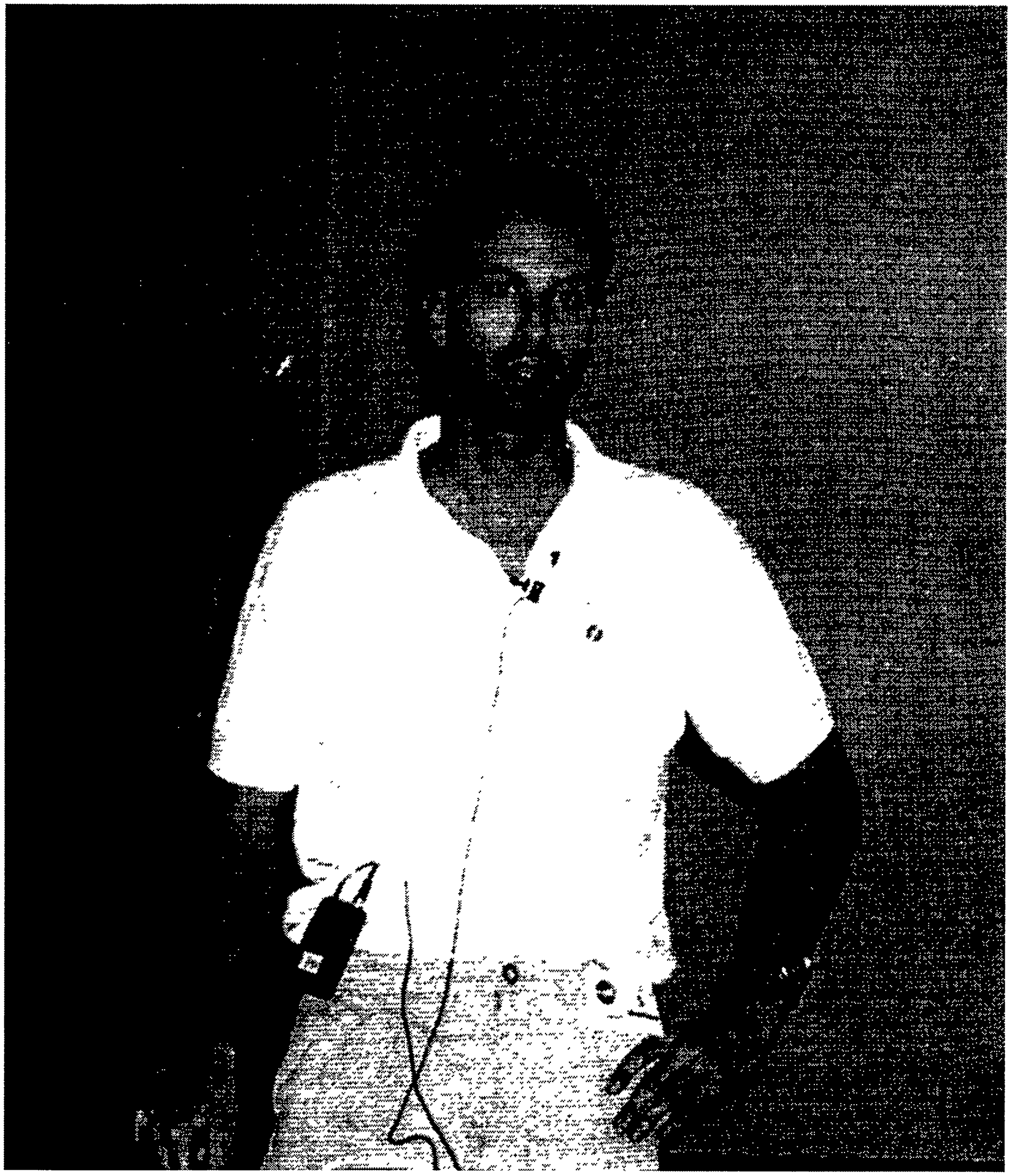

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