STARS: A PROPOSAL FOR A DEDICATED SPACE MISSION TO STUDY STELLAR STRUCTURE AND EVOLUTION

M. FRIDLUND
ESA/ESTEC, Space Science Department, Noordwijk, The Netherlands

D.O. GOUGH
Institute of Astronomy, and Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK

A. JONES
Bartol Research Institute, University of Delaware, USA

T. APPOURCHAUX
ESA/ESTEC, Space Science Department, Noordwijk, The Netherlands

M. BADIALI
IAS/CNR, Frascati, Italy

C. CATALA
Observatoire de Paris-Meudon, Meudon, France

S. FRANSEN
Institut for Fysik og Astronomi, Aarhus Universitet, Denmark

G. GREC
Université de Nice, Nice, France

T. ROCA CORTÉS
Instituto de Astrofisica de Canarias, La Laguna, Spain

K. SCHRIJVER
Lockheed - Palo Alto Research Laboratories, Palo Alto, California, USA

ABSTRACT STARS is an asteroseismological space mission, currently under Phase-A Study by the European Space Agency (ESA) as a candidate for the M3 mission. This report summarizes the conclusions of the Assessment Study; it is based on presentations made in Paris early in May 1994 to the ESA selection committees and to interested members of the scientific community.

INTRODUCTION

STARS is a mission aimed at providing an empirical framework to gain new insight into the physics of stellar evolution, and into the connexion between the interiors and the visible surfaces of stars. The mission will address basic stellar structure. It will enable us to investigate the physics of stellar interiors: for example, the equation of state, the opacity of stellar material, and energy and angular momentum transport by convection and by waves. These are all areas in which greater knowledge is required to build a really reliable theory of stellar
evolution. Stellar models are not well constrained by observations. Usually, only effective temperature and apparent magnitude are known, although in some cases we also have information about the distance, mass, surface composition and gravity. In view of the successful Hipparcos mission, however, we can expect a large database of reliable distances to be available in the near future.

For the Sun the situation has improved with the advent of helioseismology. Measured oscillation frequencies impose severe constraints on models of the present Sun, ruling out many of the suggestions that have been put forward to explain the neutrino problem. To obtain an understanding of the physical processes in stellar interiors we need seismic measurements of a wide range of stars with different properties, and in different stages of evolution. STARS is designed to provide just such an empirical base. Measurements of oscillation frequencies will put severe constraints on the variation of sound speed with radius, especially in the central parts of a star which are of the greatest importance for stellar evolution. These measurements will also enhance our knowledge of convection, enabling comparisons to be made with a range of theoretical models constructed on the basis of different assumptions. Even in cases of distant clusters, from which the data will not be of such high quality as those from the Sun, measured oscillation frequencies of a number of stars can be used to calibrate, constrain, test and improve the models.

Field stars cover the whole range of chemical abundance, and are a source of information about the early history of the Galaxy: about its age and its chemistry. Massive stars are the major source of chemical enrichment of the Galaxy. The present state of stellar modelling is such that there is an uncertainty of a factor of at least 2 in the rate of heavy-element production. Seismic calibration will reduce that uncertainty substantially. Beyond 1.5 kpc outside the solar orbit the metallicity gradient steepens, and at 5 kpc there are young stars presently forming with metallicities substantially below solar. After accounting for interstellar reddening, one might expect to find some such stars with \( m_v < 10 \) (\( m_v \) would be 7.5 if unreddened) which would be accessible to detailed seismological study. Our perception of the chronology of the Universe depends heavily on theoretical stellar models. It requires studying globular clusters in the halo, and stars within the galactic bulge. These are too faint to be observed directly by STARS. However, there are local counterparts presently in the solar vicinity which can be observed, and which are tracers of the early chemical history of the Galaxy. A major improvement to the chronology of the spherical halo, the inner halo, the bulge and the old disk is expected from the seismic constraints imposed on the helium abundances, the sizes of the convective cores and the amount of diffusion inferred particularly in metal-poor stars. Ultimately, the uncertainty in the age of the Galaxy could be reduced by a factor 3 to 5, leading to a reduction by a similar factor in the uncertainty in the value of the Hubble constant \( H_0 \). Indeed, there may be no other way to constrain \( H_0 \) so tightly.

SCIENTIFIC OBJECTIVES

Asteroseismology

Acoustic modes of oscillation impart information about the internal state of a star on the outer reflecting boundary, causing movement of the photosphere
which enables the oscillations to be observed. By measuring the frequencies of oscillation, and thereby the timbre of the acoustic tones, aspects of the structure of the star can be determined, just as a musical instrument can be identified from its timbre. But to do this requires very precise frequency measurements, which can be achieved only from the long uninterrupted sequences of high-quality data that are attainable only from space.

Resonant modes of stellar oscillation have a broad range of characteristic spatial scales. Only the largest of those scales can be observed on stars other than the Sun. Fortunately, those are the modes that penetrate deeply into the stellar cores, and therefore provide us with the most extensive information about internal structure. Extremely precise knowledge of the frequencies of those modes would enable us to gain considerable direct knowledge of the variation of the sound speed, and indirectly the temperature, throughout the stars. From this one can learn the depths of the convective envelopes of late-type stars, important to our understanding of the energy transport and the dynamics of convective overshooting, and one can learn the radii of the convective cores of massive stars, upon which the subsequent evolution to supernovae critically depends. These issues have a direct bearing on nucleosynthesis, and the chemical evolution of the Galaxy. But equally if not more important is that they provide us with an unprecedented direct check of the theory of stellar evolution, which is central to the whole of astrophysics.

Of utmost importance to our astrophysical understanding is to know the internal structure of stars chosen from over the whole of the Hertzsprung-Russell (HR) diagram, encompassing the entire range of stellar masses and ages. Relatively few stars are accessible to the detailed seismic probing that results in direct inferences of the stratification of their interiors. However, the theory of stellar evolution is sufficiently well worked out that very precise seismic calibrations would be possible using only the most basic, and most readily measurable, properties of the oscillation spectra. Such seismic data can be obtained with STARS even from the fainter, late-type stars. Those data are the mean values $\Delta$ of the differences between the frequencies of modes of like degree $l$ and varying order $n$, and the mean differences $\delta$ between the frequencies of modes of like order and varying degree. To be effective, it is essential to measure stars in clusters; the constraint that cluster stars have a common origin is crucial for enabling us to determine the gross parameters that characterize them — their masses $M_j$, helium abundance $Y$, mixing-length factors $\alpha_j$, heavy-element abundance $Z$ and age $t$ — even though the origin itself is not actually known in advance. Figure 1 illustrates how that determination improves as the number $N$ of stars increases. Notice that one obtains as a product of the calibration an improved determination of the distance $D$ to the cluster, which can be used to improve the distance scale of the Galaxy, and ultimately that of the Universe.

In addition to information about the basic hydrostatic structure of stars, STARS will determine an average of the internal angular velocity from measurements of rotational splitting of the oscillation frequencies. That will enable us to estimate stellar angular momenta, $H$, and to learn how $H$ varies during evolution. Moreover, coupled with measurements of the surface angular velocity from the Lyman $\alpha$ monitor, a measure of the rotational shear will be obtained. At present we have no reliable indicator whatever of the internal angular velocity of any star other than the Sun. The knowledge gained from STARS will transform our view of angular-momentum transport, which is
essential for our understanding not only of internal dynamics but also of the consequent implications concerning meridional advection of the products of the nuclear reactions, which ultimately controls the very evolution of the stars. The outcome will be that STARS will consolidate the theory of stellar structure and evolution to the point at which it will be an enormously more reliable basis for the rest of astrophysical research. Furthermore, it will provide a sufficiently reliable determination of the internal state of otherwise inaccessible parts of the Universe, turning them into invaluable laboratories to advance our knowledge in other branches of physics.

Fig. 1. Standard errors $\sigma(A_j)$ associated with inferred stellar parameters $A_j$ in a cluster of $N$ stars. The observations are assumed to have standard relative errors $\sigma(\ln T_{\text{eff}}) = 0.01$ in the effective temperatures $T_{\text{eff}}$, $\sigma(\ln m_v) = 0.01$ in the visual magnitudes $m_v$, $\sigma(\ln g) = 0.1$ in the surface gravities $g$, $\sigma(\Delta) = 0.05 \mu\text{Hz}$ and $\sigma(\delta) = 0.7 \mu\text{Hz}$ in the seismic parameters $\Delta$ and $\delta$, $\sigma(\ln Z/X) = 0.5$ in the composition ratio $Z/X$, where $X$ is the hydrogen abundance, and $\sigma(\ln D) = 0.1$ in the distance $D$ to the cluster. The seismic parameters $\Delta$ and $\delta$, which can be regarded as characteristic (though precisely defined) values of $\nu_{n,l} - \nu_{n-1,l}$ and $\nu_{n,l} - \nu_{n-1,l+2}$, are assumed to have been obtained from frequencies $\nu_{n,l}$ of modes with standard errors of $1 \mu\text{Hz}$, having $0 \leq \ell \leq 2$ and orders $n$ in the two ranges defined by $1 \leq n + \ell/2 \leq 14$ and $15 \leq n + \ell/2 \leq 28$; only half the modes are assumed to have been of sufficient amplitude for their frequencies to have been measured. The errors in the parameters inferred decrease rapidly as the number $N$ of stars increases.

Monitoring stellar activity

It is widely believed that in stars with convective envelopes the turbulent motion couples with the stellar rotation to drive dynamos which generate magnetic fields extending through the photospheres into the outer stellar atmospheres. The nonradiative heating associated with magnetic energy dissipation is manifest in a series of emission lines, among the strongest of which we find Lyman $\alpha$ at 121.6 nm. Monitoring the emission in this line, using a selective beam-splitter in the seismic telescope and an appropriate detector, which together form the Lyman $\alpha$ Monitor (LAM), reveals some of the important effects that magnetic activity has on stellar atmospheres. This
will supply the seismologists with information about the outer, atmospheric boundary of the resonant cavity (properly averaged over the entire star, not only over the disk as in the case of single exposures), which can affect the resonant oscillation frequencies. The association of Lyman-α emitting plages with optically dark starspots will also be helpful in the interpretation of the measurements obtained from the seismological instrument. Moreover, the LAM will determine accurate surface rotation periods (and possibly even supply evidence for surface differential rotation), even if the starspot coverage is low. These periods can be compared with seismologically determined measures of the internal rotation in, for instance, rapidly rotating cluster stars that are undergoing severe magnetic braking which leads to substantial differential rotation. With the LAM it will also be possible to study the short-term chromospheric variability in relatively bright stars.

Despite the strong interstellar extinction in light from distant stars which leaves only part of the line wings visible, the Lyman α line has been selected because a low-background photon counting detector can be used without the need of inefficient narrow-band interference filters, thus yielding a high signal-to-noise ratio for short to moderate integration times, so that even the relatively distant open-cluster stars can be monitored accurately. The proposed orbit for STARS does not subject the instrument to the geocoronal emission that has always hampered the observation of Lyman α emission in the past.

OBSERVATIONAL REQUIREMENTS AND PROGRAMME

In order to reach its scientific objectives, the STARS mission will observe oscillations of members of open clusters with a variety of different ages. A baseline scientific scenario would include seismic observations of α Per, the Pleiades, Coma, and the Hyades; but other clusters could also be added to the target list. The target list will also include binaries with good mass and radius determinations, and stars observed by Hipparcos for which good knowledge of distance will be at hand. Finally, the chosen targets must provide good coverage of the HR diagram.

The basic requirements that the targets must satisfy help to define the core programme of the mission. In addition, the concept of the STARS mission includes a Guest Investigator programme. Observations with STARS will be of major interest to a very large scientific community, and a wide range of stars that are of some particular interest can be included in the list of targets, such as δ Scuti stars, rapidly oscillating Ap stars, white dwarfs, RR Lyrae, β Cep, Am and λ Boo stars. Other investigations will also be possible, such as studying microlensing and seeking stellar companions.

The basic requirement of the mission is the measurement of solar-like oscillations in a sequence of open clusters. G-type stars in α Per have typically $m_v = 11$. If we assume that the oscillation amplitudes are of the same order as those of the Sun, then the measurements must suffer photometric noise no greater than 0.8 ppm down to 11th magnitude in order for the oscillations to be detected at 3σ. To obtain a precision of the frequency measurements sufficient to perform the analysis described above (typically 0.2 – 0.4 μHz), a total integration time longer than about 1 month will be spent on each target. Sidelobes due to gaps in the data will be avoided by ensuring a duty cycle greater than 95%.
With such a requirement, sidelobes will remain below photon noise for most of the mission’s targets.

Finally, in order to measure a sufficient number of stars, and in particular a sufficient number of open-cluster members, during the nominal 2-year lifetime of the mission, the instrument has been designed to be capable of observing simultaneously all stars in a $1^\circ \times 1^\circ$ field. The observation strategy of STARS will be to remain pointed towards a given field, whether or not it belongs to an open cluster, for at least 1 month. Occasionally, longer integration times will be used.

As an example of target selection, we may assume that we shall want to maximize the number of observed members of the 4 open clusters listed above. Given the pointing constraints imposed by the payload accommodation, these 4 open clusters will be observable for a total cumulative time of 14 months in a 2-year lifetime, allowing the observation of more than 150 open-cluster members. Including the remaining 10 months of observations, we find that a total of about 120 stars brighter than $m_\nu = 8$ can be observed, for which a relative photometric precision better than 0.2 ppm can be obtained. The observed fields would contain more than 2500 stars brighter than $m_\nu = 11$, for which the expected photometric precision better than 0.8 ppm will be sufficient to measure solar-like oscillations, and more than 20000 stars brighter than $m_\nu = 15$, for which a photometric precision better than 5 ppm will be attainable.

PAYLOAD

Telescope
The constraints imposed by the scientific requirements on the optical elements can be satisfied as follows:

- Focal ratio f/3
- Effective diameter 0.8 m
- All-reflective axially symmetric telescope
- Field of view (FOV) 90 arcmin dia, (encompassing a square FOV of $1^\circ \times 1^\circ$)
- Point spread function (PSF) < few arcsec; uniform shape of the PSF
- Planarity of the focal surface; unvignetted FOV, protected from straylight

Our way of achieving simultaneously a wide field of view, a flat focal surface and an appropriate level of focussing of the stellar images in every region of the FOV is to use three reflecting surfaces, every one with correcting figuring, i.e., a Triply Reflecting Telescope (TRT). The proposed configuration uses the main mirror both for the first and the third reflection, thereby achieving compactness of the instrument. In the proposed TRT, the first and third reflections occur in separate zones of the main mirror: the third reflection occurs in a central zone, the first in a surrounding annulus. The instrument is contained in a cylinder of sandwiched carbon-fibre reinforced plastic (CFRP) of diameter 1.115m and height 0.94m. The overall height of the instrument, including the external baffles, is approximately 1.5m

The beam splitter

The beam splitter may be a multi-layer coating on a (glass) substrate. Such a reflecting surface can reach an efficiency around Lyman $\alpha$ of approximately 50%. The manufacture of a beam splitter with a sufficient area for the purposes of STARS poses no problem. The presence of the beam splitter will not affect
the asteroseismological results adversely, because (i) it transmits virtually all the visible radiation, (ii) the region covered by the rays from any single star at the location of the beam splitter is large (owing to the fast focal ratio) in comparison to the expected pointing fluctuations, so that short-term transmission variation due to satellite motion is very small, and (iii) the CCD detector for asteroseismology is positioned such that the image is slightly defocussed, so that any ghost images caused by multiple reflections in the beam splitter lie within the 40-pixel-diameter area over which the image of each source is spread.

The photometric detector
The requirements of this detector are:
- Large imaging area
- Very high stability
- Large dynamic range

These are well satisfied by a CCD detector. The defocussing of the image, spreading the photons from a single star effectively over some 800 pixels, will enable the detector to handle the large flux from even the brightest objects in the programme foreseen for STARS. It will also permit signal ‘binning’, thereby decreasing the readout time. In order to maintain a wide field of view we envisage a detector constructed of four buttable CCD arrays. The CCD chips would be custom made with 24 µm square pixels in a 1024 × 2048 format. Half the pixels are masked, giving an imaging area of 1024 × 1024 pixels, so that a frame-transfer strategy can be used. As the time for frame transfer is short, no mechanical shutter is needed; that simplifies the mechanical design of the camera, optimizes the duty cycle, and increases reliability. Each chip will have two readout amplifiers, enabling eight parallel electronic chains to speed the readout and to provide some redundancy.

MPP (multi-phase pinned) operation of the CCD chips is preferred to ensure good performance in space. Although this reduces the full well capacity, there is flexibility enough in the readout scheme to compensate without losing the possibility of observing bright objects. The detector operates at a temperature below −50°C regulated to within ±0.1°C. The system is photon-noise limited, with the noise well below the 0.8 ppm limit mentioned above.

A fairly advanced set of processing modes are being designed to reach the high goals set for the photometry. A small number of processors will handle reductions, either in parallel, or in a pipeline, or in a combination of the two. The whole system, from the CCD arrays to the final processing elements, requires no technical development. The most advanced element is probably the software, which must be fast and flexible.

The activity monitor
The Lyman α Monitor (LAM) obtains its light from the main telescope via a dichroic beam splitter. There are two possible detector configurations: in the first, the light arrives directly on a micro-channel plate (MCP) stack, provided that an edge filter can remove photons longward of about 130 nm (so that no continuum contamination will occur for stars cooler than late B or early A); in the second, the light first hits a KBr cathode; only photons shortward of about 130 nm will release an electron from such a cathode. The effective area of the telescope at Lyman α (121.6 nm) is $A_{\text{eff, Ly} \alpha} \approx 500 \text{ cm}^2$, and the relatively high energy of the Lyman α photons permits the use of a photon-counting detector with low background. Integration times needed to reach a signal-to-noise ratio
of approximately 50 for solar-type main-sequence stars with rotational velocities
typical of the stellar clusters of the core programme range from about 10 minutes
for the Hyades cluster \(m_v(G2\ V) \approx 8\) up to 2 to 4 hours in the \(\alpha\) Per and the
Pleiades clusters \(m_v(G2\ V) \approx 11\).

If the light is directed onto the detector directly, the intensifier tube might
consist of a UV-transparent \(\text{MgF}_2\) window onto which a \(\text{CsI/CsTe}\) split photocathode has been deposited. If a \(\text{KBr}\) anode is used as a long-wavelength
‘filter’, this anode will be placed obliquely behind a UV-transparent (e.g. \(\text{MgF}_2\))
entrance window, and the photoelectrons will then be directed magnetically
onto an MCP stack within the same housing. The detector will have a positional
resolution of less than 20 \(\mu\text{m}\) at Lyman \(\alpha\) (namely \(9''\), comparable with both the
characteristic scale of the PSF and the relative pointing error of the telescope
over an interval of 15 min.). The background count rate is no greater than about
\(3 \times 10^{-6}/\text{pixel/sec}\) (estimated from in-orbit EUVE observations), sufficiently low
to yield good signal-to-noise ratios.

Since STARS will not pass through the radiation belts after the detectors
have been switched on, radiation damage to the photocathode is expected to be
small. The LAM will be switched off during major solar flares.

\[\text{Fig. 2. An exploded view of the payload of STARS. The numbers refer to}
(1) location of photometric detector, (2) location of LAM, (3) outer section
of main mirror, (4) inner section of main mirror.\]
THE SPACECRAFT

The STARS spacecraft (S/C) consists of two major modules: the Service Module (SM) and the Payload Module (PM). The PM is essentially the telescope, with its associated focal-plane instrumentation in the upper part of the tube, and its electronics boxes on the SM. The SM is a tri-axis stabilized bus. The total launch mass for STARS will be 1208 kg if ZERODUR (Schott trade name for a zero-thermal-expansion-coefficient ceramic material) or ULE (ultra-low expansion) mirrors are used, and 1088 kg if SiC mirrors are adopted instead. The thermal control system is passive and is based on multi-layer insulation (MLI), radiators and appropriate surface finishes. The PM has three interfaces with the SM, one of which is a standard MACS-bus (Modular Attitude Control Subsystem) interface device embedded in the PM computer to supply startracker information for the fine attitude control of the S/C.

MISSION SYSTEM AND DESIGN

The operational lifetime must be at least two years, with consumables allowing for an extended lifetime of 5 years. The observing mode for STARS consists of a number of pointings separated by observing intervals of typically 1-month duration, during which time the S/C remains in a fine-pointing mode with a duty cycle greater than 95%. The angle between the optical axis of the telescope and the direction of the Sun will always be greater than 60°. The sky coverage of STARS must be such that the previously defined goals can be reached within the nominal lifetime of the mission. The absolute pointing error will be less than 90 arcsec. The Relative Pointing Error (RPE) is 3 arcsec over 1 second (of time) and 6 arcsec over 15 minutes, and the Absolute Pointing Drift (APD) will be 30 arcsec over a period of 1 month. These limits will permit the necessary photometric precision to be achieved.

The telescope will be used as a fine startracker for the S/C AОCS (Attitude and Orbit Control Subsystem), and its Instrument Line of Sight (ILS) with a square FOV of 1°×1° will be the reference axis. The cooling of the CCD detector to lower than −50°C will be passive.

The launch is assumed to be initially into geostationary transfer orbit (GTO) by Ariane 5 in a multiple configuration with STARS located in the SPILMA (Structure Porteuse Interne Lancement Multiple Ariane). The S/C will be moved to its final Earth-Moon L5 orbit by means of its on-board propulsion system. The total velocity increment ΔV required is 850 m s⁻¹. The preferred orbit is marginally unstable; orbital maintenance requires a further 4 m s⁻¹ of ΔV per year. The launch can take place within the daily launch window for GTO, with no seasonal constraints.

MISSION MANAGEMENT, SCIENTIFIC OPERATIONS AND ARCHIVING

STARS is a PI mission with a significant Guest Investigator Programme (GIP). It is envisaged that the PI's will have a guaranteed allocation of 30% of the available observing time, with the rest being used for the GIP. ESA will be responsible for the overall mission and S/C design, integration of the payload onto the S/C bus, system testing, launch, operations and transmission of raw data to an Output Consortium (OC). The payload will be provided by PI teams, funded by ESA member states and selected through an Announcement
of Opportunity (AO). Two possibilities for the AO are considered. One includes the telescope (+ beamsplitter), the photometric detector and the LAM. In the second, ESA will be responsible for the telescope with its associated structure, and the PI's will procure the two detectors and associated optics. Because of the unique nature of the STARS mission, the observations are to be preprogrammed at least 1 – 2 years in advance. Thus, there appears to be no need for a Science Operations Centre (SOC) in the ordinary sense. Data are expected to be downloaded to the ground station (ESOC) during the visibility period each day, and transmitted to the OC on a dedicated link. Here data are reduced, checked and transmitted to the appropriate scientific investigator. The OC also has the responsibility of preparing and delivering to ESA the archived data which will be available to the general community 1 year after they have been received by the scientist who originally proposed the observations. A small ESA team, under the project scientist, will lead and coordinate these activities, as well as being in charge of the spacecraft pointings. To assure the scientific quality of the observations, an organisation of the following kind is suggested:

A first call for proposals to both PI's and the community (2 years or more before launch) will result in a number of applications which will be screened by a Time Allocation Commitee (TAC) which will draw up a list of scientific priorities. This list will be transmitted to an Input Consortium (IC) which will have the duty of drawing up a list of pointings (15 – 25) for the first two years, with a view to maximizing the overall scientific return. This target list will be made known to the community, who can then propose secondary objectives within each field. These proposals will again be screened by the TAC. It is expected to find between 200 and 1000 scientifically worthwhile targets per field. The substantial time allowed for the selection process is motivated in part by the not insignificant ground-based supporting programme that will be needed (e.g. high-resolution spectroscopy of many of the targets).