MONS ON THE DANISH RØMER SATELLITE: MEASURING OSCILLATIONS IN NEARBY STARS

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Abstract

MONS (for Measuring Oscillations in Nearby Stars) is the scientific project on the Danish Rømer satellite mission, which is being developed as part of the Danish Small Satellite Programme. The principal goal is to study solar-like oscillations in around 20 bright stars, with a precision that in the best cases will be limited only by the intrinsic stellar ‘noise’. The baseline orbit, a so-called Molniya orbit, allows access to essentially the entire sky during the planned 2-year mission. The main instrument is a short-focus reflecting telescope with an aperture of 32 cm, making two-colour measurements. A focused Field Monitor will be used to detect and correct for possible faint variable stars of substantial amplitude near the main target. In addition the Field Monitor, and the Star Trackers on the platform, may be used to observe a broad range of variable phenomena. The project has concluded the Systems Definition Phase by a successful review, and launch is scheduled for the middle of 2005.

Key words: Stars: structure, oscillations – asteroseismology – high-precision photometry

1. Introduction

Denmark launched its first national satellite, Ørsted, in 1999; the purpose of this mission is to make very accurate measurements of the Earth’s magnetic field. The satellite is still (October 2001) operational and has provided a number of very important results, including a revised model of the Earth’s magnetic field (Olsen et al. 2000). As a follow-up to the successful development of this mission, it was decided in 1997 to establish a Danish Small Satellite Programme, initially funded for the four-year period 1998 – 2001.

The call for mission ideas within this programme, and the further more detailed applications and evaluation, led to the selection of a mission consisting of two projects:

– MONS, to study solar-like oscillations in other stars
– Ballerina, to detect gamma-ray bursts and observe them with an X-ray telescope.

The proposal, by the committee under the Danish Research Councils which is responsible for the programme, to combine these two missions resulted from a communality of features, including the orbit, and the expectation that the combined mission would fit within the constraints of the programme. It was also stated by the committee that, if the combination turned out to be infeasible, the MONS project had the highest priority and should be carried out on its own. The combined mission was named Rømer, after the Danish astronomer Ole Rømer (1644 – 1710); he was the first to measure the finite speed of light and he made major developments of astronomical instrumentation.

The System Definition Phase of the combined mission was started early 2000, by a combination of Danish industries and research institutions. An important early goal was to establish whether or not the combined mission was feasible. At a mid-term review in October 2000 it was concluded that, although technically possible, the combined mission was too complex, and likely too demanding in terms of mass and finance, to be realistic within the Small Satellite Programme. Thus it was decided to continue with a mission involving only the MONS project; however, the name Rømer was kept for this mission. Figure 1 illustrates the current configuration of the satellite.

Figure 1. Artist’s impression of the Rømer satellite in orbit.
The goal of the MONS project is to probe the interiors of stars through observations of oscillations in their intensity and colour. Thus the mission extends the very successful studies of the solar interior over the last decade through helioseismology (for a review see, for example, Christensen-Dalsgaard et al. 2000). The frequencies of oscillation will provide information about the structure and rotation of the stellar interiors, and hence allow investigation of effects of stellar evolution and the physical properties of matter in the stars. The main targets for the mission are stars that show oscillations similar to those observed in the Sun. Since the amplitudes of such oscillations are typically of order a few parts per million (ppm) an overriding requirement on the project is photometric precision; the design goal is that the instrumental and photon noise should be substantially below the intrinsic stellar granulation noise for the brightest objects on the target list. MONS will observe solar-like oscillations in 15 – 20 stars. In addition, high-precision photometry will be carried out on a few other carefully selected variable stars. Sufficient frequency resolution requires that each target be observed almost continuously for about one month. Also, the primary targets are distributed over the whole sky, and hence an orbit allowing access to the entire sky is highly desirable. Given the budget of the programme, launch has to be obtained as a passenger on a larger mission. Thus it was decided to keep the satellite within the ASAP-5 restrictions, which is being established as a de-facto standard for such secondary launches. Thus the dimensions of the satellite are limited to 60 by 60 by 71 cm, with a total mass below 120 kg.

The primary observations will use the MONS Main Telescope, a strongly defocussed 32-cm telescope observing in two colours. However, the satellite will also carry other instruments permitting a broad range of parallel science. The MONS Field Monitor has as primary goal to detect and correct for faint variable stars near the main target; such stars, within the field of the Main Telescope, might otherwise corrupt the data. The Field Monitor has an opening of 5 cm and a field of $5^\circ \times 5^\circ$, which is observed in focus. Thus it allows the nearly continuous monitoring of the large number of other objects in the field, undoubtedly including variable stars of various types as well as other time-varying astrophysical objects. Data for an even larger field, although with lower precision, will be obtained from the Star Trackers, whose main purpose is to determine the orientation of the satellite. Two Star Trackers will be included, pointing in the same direction as, and the opposite direction to, the Main Telescope. The Star Trackers have a 2.4 cm aperture and cover a field with a diameter of $22^\circ$.

The Rømer satellite is predominantly a Danish mission, with the scientific and technical responsibility, as well the overall design and construction of the satellite, being located in Denmark. The scientific headquarters of the mission are at University of Aarhus, the prime industrial contractor is the company Terma A/S (see [http://www.terma.com](http://www.terma.com)) and the overall management is carried out at the Danish Space Research Institute. However, the project involves very important international contributions. The design and construction of the Main Telescope will be carried out by the Australian companies Auspace and Prime Optics, while the optics and other hardware for the Field Monitor is provided by Spain and Belgium. Also, Finland will provide the platform computer, while contributions to the onboard software development come from Belgium. Finally, the scientific preparations for the mission and the utilization of the data involve the broad MONS Science Consortium, with around 150 members in 20 countries.

2. Primary scientific goals

Observations of stellar oscillations provide information on many aspects of the stellar interior. The frequencies of the oscillations depend on the structure of the star, particularly the distribution of sound speed and density, and on gas motion and other properties of the stellar interior. The amplitudes of the oscillations are determined by the excitation and damping processes, which may involve turbulence from convection, opacity variations and magnetic fields. The best targets are stars which oscillate in several modes simultaneously. Each mode has a slightly different frequency, reflecting spatial variations of the structure within the star, and the combination places strong constraints on the internal properties. (For reviews of such studies see Brown & Gilliland 1994; Gautschy & Saio 1996; Christensen-Dalsgaard 1998; Gough 1998.)

Stellar oscillations are standing waves which reach deep inside the star, and they are observed via their effect on the surface. To a very good approximation, the surface pattern of a single oscillation mode can be described by a spherical harmonic, which is characterized by two quantum numbers: the degree $l$ and the azimuthal order $m$; $l$ determines the horizontal wavelength, while $m$ measures the number of nodes around the equator. In addition, a mode is characterized by the radial order $n$, which roughly corresponds to the number of nodes in the radial direction. In practice, for stars apart from the Sun we measure averages over the stellar surface, thus effectively suppressing modes with comparatively high degree and hence short wavelength. In general, stellar observations are dominated by the modes of the lowest degrees ($l = 0, 1, 2$ and 3). Fortunately, these are the most useful for probing the interior because they reach deepest below the stellar surface.

The principal targets for the MONS Main Telescope are stars with oscillations similar to those observed in the Sun. These are believed to be excited stochastically by the effects of convection in the near-surface layers of the star, where the speed of convective motion approaches the sound speed, leading to an efficient generation of sound waves. These waves couple to the normal modes of the
star, leading to oscillations which can be observed in, for example, the luminosity and surface temperature of the star. This mechanism is expected to cause oscillations in relatively cool stars with substantial near-surface convection; these include stars in the phase of central hydrogen fusion with masses up to around $1.7 M_\odot$, $M_\odot$ being the mass of the Sun. Due to the broad-band nature of the mechanism most modes in a fairly broad range of frequencies are expected to be excited, as is indeed observed in the Sun. This substantially simplifies the identification of the modes and the analysis of the frequencies. Unfortunately, the expected amplitudes are extremely small: a few parts per million (ppm) in relative fluctuations in luminosity or surface temperature.

The observed modes are concentrated in a frequency range between 2 and about 4.5 mHz, corresponding to periods between 8 and 4 minutes. (Other observations show that the solar oscillation spectrum extends to frequencies below 1 mHz.) These modes are acoustic modes of high radial order which, according to asymptotic theory, are essentially uniformly spaced in frequency, as is indeed observed. It should be noticed that the observed amplitudes are substantially higher in the blue than in the red wavelength region. This is the background for using colour as the primary observable with the MONS Main Telescope: the ratio between blue and red intensities still shows a substantial oscillation signal, while certain contributions to the instrumental noise are strongly reduced. It should also be noted that the ‘noise’ background in Fig. 2 is in fact of solar origin: it arises from the intensity fluctuations caused by granular motion at the solar surface.

Details of the solar spectrum are illustrated in Fig. 3. It is characterized by the large frequency separation $\Delta \nu_l = \nu_{nl} - \nu_{n-1\ell}$ between modes of adjacent radial order $n$, corresponding to the almost uniform spacing shown in Fig. 2, and the small frequency separation $\delta \nu_l = \nu_{nl} - \nu_{n-1\ell+2}$; here $\nu_{nl}$ is the cyclic frequency of a mode of radial order $n$ and degree $l$. The small separation is substantially influenced by the sound speed in the core of the star and hence is sensitive to the chemical composition there; since the core composition changes with age, as hydrogen is converted into helium, $\delta \nu_l$ provides a measure of the evolutionary state of the star. On the other hand, $\Delta \nu_l$ depends on the overall properties of the star.

These properties have important consequences for the diagnostic potentials of the frequencies: by observing $\Delta \nu_l$ and $\delta \nu_l$ it is in principle possible to determine both the mass and age of a star. In practice, the determination is evidently dependent on other uncertainties in stellar properties. These issues are discussed in more detail by Gough (these proceedings) and Monteiro, Christensen-Dalsgaard & Thompson (these proceedings).

Detailed observations of accurate frequencies offer far more information about the stellar interior, allowing inferences beyond the basic parameters of the star such as mass and age. For example, the location of the base of the convective envelope introduces an oscillatory signal in the oscillation frequencies which may be used to constrain the depth of the convection zone and the properties of the region below it (Monteiro, Christensen-Dalsgaard & Thompson 2000; Monteiro et al., these proceedings). Also, Pérez Hernández & Christensen-Dalsgaard (1998) found that the ionization of helium affects the sound speed and hence the oscillation frequencies of stellar models in a manner that is in principle observable; this may be used to determine stellar abundances of helium, a quantity that

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{solar_spectrum.png}
\caption{Small section of the solar spectrum (lower panel of Fig. 2), showing $(n,l)$ values for each mode. The large and small separations are indicated. These measure the average density and core composition, respectively, and can therefore be used to infer the mass and age of a star.}
\end{figure}
is otherwise only poorly known. With sufficiently good data it may be possible to carry out inversions for stellar structure, at least in parts of the star or under additional assumptions (see Basu, Christensen-Dalsgaard & Thompson, these proceedings; Roxburgh, these proceedings; Thompson & Christensen-Dalsgaard, these proceedings).

Estimates of the amplitudes expected for solar-like oscillations have been made, assuming stochastic excitation by convection and calibrating against the solar amplitudes (e.g. Christensen-Dalsgaard & Frandsen 1983; Houdek et al. 1999). Kjeldsen & Bedding (1995) pointed out that the results roughly indicated that the amplitudes were proportional to the ratio $L/M$ between the stellar surface luminosity and mass. Recent observations of solar-like oscillations (Kjeldsen et al. 1995; Marti´ c et al. 1999; Bedding et al. 2001; Bouchy et al. 2001) indicate that the amplitudes increase less rapidly with increasing effective temperature, but show the predicted increase with luminosity at solar effective temperature. Nevertheless, these observations provide confidence that MONS will indeed be able to make detailed observations of oscillations in a substantial range of stars.

Although the main emphasis will be on solar-like oscillations, the MONS Main Telescope will also be used to observe a few stars known from ground-based observations to pulsate. Theory suggests that in these many more modes may be excited than currently observed, likely at amplitudes rendering them undetectable from the ground. Important examples are the $\delta$ Scuti stars and the $\beta$ Cephei stars, which together cover an extended range in mass, and hence interior properties, along the core hydrogen-burning main sequence. If such low-amplitude modes can indeed be detected, the MONS observations may provide very valuable information about the properties of the stars. Additional data on such ‘classical’ pulsating stars will be obtained with the Rømer Star Trackers and the MONS Field Monitor (cf. Section 3).

In addition to stellar structure, the frequencies of oscillation depend on the rotation of the star. This gives rise to a frequency splitting according to $m$ which, to lowest order, can be roughly written as

$$\nu_{nlm} = \nu_{nl0} + m \frac{\langle \Omega \rangle_{nl}}{2\pi} ,$$

where $\langle \Omega \rangle_{nl}$ is an average of the angular velocity weighted by the structure of the given mode. When only low-degree modes are observed, as will be the case for MONS, these averages all extend over most of the star. However, even such limited information will give some indication of the variation of rotation with depth in the star, particularly if it is combined with measurement of the surface rotation via intensity variations induced by spots, which MONS will easily detect. Measurement of the rotational splitting requires observations over a period that somewhat exceeds the rotation period. Thus MONS will be able to measure the splitting for stars rotating at least as fast as the Sun, with rotation periods below 25 days.

3. Payload

The primary requirement on the payload and platform is to allow measurements of oscillations in intensity or colour at the sub-ppm level over a one-month observing sequence, in the frequency range relevant to stellar oscillations. To achieve a sufficiently low photon noise, and hence sufficiently large number of photons, with current CCD detectors strong defocusing is required. As a result, the Main Telescope cannot distinguish between the bright primary target and possible faint near-by stars varying with substantial amplitudes; to correct for this, the payload includes a focussed Field Monitor which can detect such variables and correct for their influence.

3.1. MONS Main Telescope

The telescope aperture, together with the optical and detector efficiency, determines the photon noise, which evidently has to be minimized. The dimensions of the telescope are limited by the overall size of the satellite which in turn are constrained by the restrictions of launch opportunities. This determines the length of the telescope; as discussed in Section 3 the diameter is then effectively limited by the constraint that the Earth exclusion angle be at most 30°; this has led to a telescope diameter of 32 cm and a telescope with an f-ratio of 0.9.

![Figure 4. Schematic design of the MONS Main Telescope. The field stop is mounted on the conical baffle which is bolted to the main mirror, to ensure mechanical and thermal stability. The CCD is cooled through a heat pipe connected to the radiator panel.](image-url)

It should be noted that for relatively rapid rotation the effects on the frequencies are substantially more complicated; see, for example, Soufi et al. (1998).
Light will be detected by means of a CCD detector. The total number of photons detected is therefore limited by the well depth of the detector; to reduce the photon noise the stellar image is defocused to an outer diameter of 9 mm. To reduce sensitivity to guiding errors the point-spread function must be uniform to 1 – 2% over small scales. Effects of scattered light are minimized by passing light from the star through a field stop, placed at the focal position, with a diameter of less than 1 mm. The field stop is mounted on a conical baffle directly bolted to the primary mirror; mirror and baffle are made of aluminium, so that temperature changes will not change the relative dimensions of the optical system. The overall telescope design is shown in Fig. 4.

To reduce instrumental noise it is highly desirable to carry out differential photometry. This is achieved in the present design by measuring differentially between light in two wavelength bands (red and blue) from the target star; since the oscillation amplitude is substantially higher in the blue waveband than in the red band (cf. Fig. 2), the ratio between the two intensities contains an oscillation signal. The separation into two bands is made by placing a filter, divided into red and blue segments, at a suitable point in the optical path; as a result, the two bands are measured simultaneously on the same detector, ensuring the full advantage of the differential measurement, although at the expense of some loss of light. A schematic view of the detector plane is shown in Fig. 5; note that the defocussed image fills a large fraction of the CCD.

The baseline CCD detector has an active area of 1k × 1k pixels, with frame-transfer readout. It is cooled passively to a temperature of −90°C, by connecting the detector by means of a cold finger to a cooling plate. The temperature will be kept stable to 0.1°C through a small heating element and measured to a precision of 0.01°C for later decorrelation during data analysis. The expected noise level in the measurement of the colour ratio, assuming a 30-day observing sequence, is illustrated in Fig. 6. This satisfies the goal of reducing the measurement error to be below the expected intrinsic stellar ‘noise’ for the brighter targets.

### 3.2. MONS Field Monitor

The field stop of the MONS Main Telescope lets through light from a region with a diameter of around 11 arcmin on the sky. Thus the defocused image on the detector will contain contributions from all stars within such a region around the main target. Large-amplitude variations of a faint source could be mistaken for oscillations of the target. Although it would in principle be possible to test against this by means of contemporaneous ground-based observations, the effort required to do so would in practice be unrealistic. Therefore we have included a small focused telescope to monitor the field around the target. The requirements for this Field Monitor can be estimated by noting that if a magnitude difference of at least \( \Delta V = 6 \) is assumed between the target and the neighbouring stars, the required photometric precision for the target translates into a noise level of at most 125 ppm in the amplitude spectrum after 30 days, in the Field-Monitor observations of a \( V = 10 \) star.

The MONS Field Monitor consists of a lens assembly with an aperture of 50 mm, with a 1k × 1k CCD detector that gives a field of 5° × 5°. Since the precision require-
ments are less stringent than for the Main Telescope, so are the requirements on cooling of the detector; it will be maintained at a temperature of around $-20^\circ$C. The current design is illustrated in Fig. 7.

We note that the large focused field of the Field Monitor lends itself to very interesting possibilities for parallel science. In addition to the observations required for the primary science, data on selected stars in the field will be recorded at a rapid cadence, to investigate other types of pulsating stars. Furthermore, the image of the complete field will be accumulated and transmitted to the ground at a lower rate, at least several times per orbit, to allow search for transient phenomena in a large number of objects. The photometric capabilities of these observing modes are illustrated in Fig. 8. Possible targets for parallel science are discussed in Section 7.

4. Platform

The Systems Definition Phase of the Rømer project led to the conceptual design of the satellite illustrated in Fig. 9. The overall dimensions are $60 \times 60 \times 71$ cm and the mass, including a 25% margin, is around 100 kg, well below the limit set by ASAP-5 constraints. In operation, the satellite will be oriented such that one diagonal points towards the Sun; thus two sides are covered with solar panels, while the other two sides, which are permanently cold, carry the cooling plates for the CCD cameras. The lid, which is closed during launch, protects the main telescope against direct sunlight. The solar cells allow an average power consumption of 55 W.

The satellite is three-axis stabilized, controlled by four momentum wheels. Momentum dumping will be made through magneto-torquing, by means of magnetic coils coupling to the Earth’s magnetic field, during the parts of the orbit that are sufficiently close to the Earth. Attitude control is maintained by means of two Star Trackers, of which generally only one is operational at any given time. Additional coarse attitude information is obtained from Sun sensors and a magnetometer. The expected attitude stability during observations is better than 10 arc sec.

The platform is controlled by a single Command and Data Handling computer, with a separate computer managing the payload and taking care of the on-board data processing. The various components are connected by a dual redundant CAN bus. For communication the satellite carries two S-band antennas, with a transmission power of 2 W. The baseline is to use a single ground station, located in Denmark, with a 1.8-m antenna; this allows a average data rate of 24 Mbyte/day, sufficient for both the primary and parallel science.
5. Orbit and operations

The targets for a modest asteroseismic mission like MONS are generally bright stars, for which the most precise measurements can be made. This furthermore has advantages in terms of the determination of other properties of the stars: bright main-sequence stars are relatively nearby and hence have accurate determinations of their distances; and because they are bright, their spectroscopic properties can be determined in great detail.

The disadvantage of the restriction to bright stars is that the selection of stars is somewhat limited. This is particularly constraining since, in addition, it is important to observe as wide a range of stellar properties as possible, as discussed in more detail in Section 4. Thus it is highly desirable to organize the mission, including most importantly the choice of orbit, such that all parts of the sky can be observed at some time during the mission. Needless to say, this has to be balanced against the constraints implicit in a small-satellite mission, in terms of cost and operational simplicity.

From a scientific point of view, the requirements are that the relevant targets must be observable at least for one 30-day period during the baseline two-year mission, the observations being, as far as possible, without substantial interruptions. Also, the effects of scattered light from the Sun and Earth (and, to lesser extent, the Moon) on the observations with the Main Telescope must be minimized. In addition, a number of technical constraints must be satisfied. A part of the orbit must go through a region of the Earth’s magnetic field which allows momentum dumping with magnetorquers. This requires a low perigee and a sufficiently high orbit inclination. Also, part of the orbit must be close to the Earth, preferably within view of Denmark, to simplify data transmission and control of the satellite. The orbit must provide sufficient solar radiation on the solar panels during the observing modes. The use of a Star Tracker must be possible, without interference from the Sun or Earth, for all the relevant targets. And finally, the constraints on cost clearly mean that an orbit must be chosen where the satellite can be launched as a passenger.

In practice, the constraints on the Earth mean that light from the Earth should never directly reach the main mirror of the MONS telescope during observations. Similarly, for the Star Trackers the Earth should be outside an exclusion angle which depends on the length of the baffle and other design aspects.

Based on these considerations, the baseline orbit has been chosen to be a so-called Molniya orbit, whose main characteristics are summarized in Table 3; such orbits are used for Russian communication satellites, and hence launch opportunities arise at regular intervals. It is characteristic of the orbit that apogee is at high northern latitude. Thus light from the Earth is potentially troublesome for observations of objects on the southern sky. Following a trade-off analysis, dimensions of the Main Telescope have been chosen such that the Earth exclusion angle is 30° (cf. Section 3.1). Given this, the possible sky coverage during the mission can be determined, depending on the time of launch. An example is illustrated in Fig. 9, here also is shown the location in the sky of the highest-priority targets for the main telescope (cf. Section 4). Due to the precession of the orbit, the exclusion region shifts through about 7 hours in right ascension during the two-year mission. Thus, with a suitable choice of the time of launch it will be possible to observe all key objects during the baseline mission.

Given the exclusion angle of 50° of the Star Trackers, observation of southern objects with just one forward-pointing Star Tracker would be essentially impossible. Thus the baseline satellite configuration has two Star Trackers, pointing in the same and the opposite direction as the Main Telescope. Only one of the Star Trackers need be operated at any given time for the primary science programme, although the parallel science may benefit from having both operating.

Passage through the Earth’s radiation belts is an unavoidable consequence of the requirements of a high apogee and a low perigee. For the Molniya orbit this effect is to some extent reduced by the high inclination, but not eliminated. This results in requirements on the radiation shielding which can, however, readily be met within the mass budget of the satellite. Another consequence is that the observations are interrupted during passage through the radiation belts. We estimate that the resulting duty cycle is around 85 %; except for very special cases this has minimal consequences for the quality of the data, compared with a duty cycle of 100 %.

Figure 9. Two different views of the Rømer satellite conceptual design. The left-hand image shows one sunpointing side (covered with solar panels and with one of the antennas) and one cold side; note the (partly hidden) Main Telescope and the square baffle of the Field Monitor. The right-hand image shows the two cold sides, with radiator panels to cool the CCD cameras; also visible is the round baffle of the forward-pointing Star Tracker.
The mission is very simple: for most targets the demands of frequency resolution and signal-to-noise ratio require extended and nearly continuous observations of each target. Thus the baseline is to observe each target for at least 30 days, or 60 orbits. Selected particularly important targets may be observed for 100 orbits.

For particular targets considerably shorter observing periods (although always at least one orbit) may be used. These include eclipsing binaries and planet transits; here the precise time of the relevant event can be predicted well in advance, and the duration of the event is typically less than one orbit. Such observations will be scheduled, as far as possible, between the main long-duration pointings. However, in exceptional cases it may be possible to interrupt the long pointings for a single orbit, without substantial effect on the data quality.

### 6. Preliminary target list

When assigning priorities to solar-like targets for the MONS Main Telescope, consideration must be given to the expected signal-to-noise, as well as to the desire to cover an interesting range in stellar parameters. The relevant stellar properties include mass, evolutionary stage, content of heavy elements (conventionally known as metals), and rotation rate. In some cases identification of stars with the desired property, while still observable with MONS, presents some difficulties; in particular, metal-poor stars are fairly rare and therefore tend to be rather distant and hence difficult to observe. Also, it may happen that a star is potentially very interesting, but of uncertain observability. In such cases further studies, either from the ground or with brief observations with the MONS Main Telescope, may be required for the final selection.

Target selection has been based on an extensive list of stars of sufficient brightness to be observable with MONS and of the appropriate spectral type. These were then analysed in terms of their properties, as well as for the expected amplitude and observational noise, and discussed in the MONS Principal-Investigator team. The result was the preliminary list of targets presented in Table 2, with stars grouped according to properties and divided according to the following priorities:

1. Very high priority. Should definitely be observed.
2. High priority. Should be observed.
3. Excellent target. Should be observed.

The 2b and 3b groups contain stars which are very interesting, but which may not show solar-like oscillations because of S/N limitations, or because they are too hot. These stars could be checked out for one or two orbits to determine feasibility.

The present target list is based on current information about the stars, as well as on our present understanding of the excitation of the oscillations. The stars of priority 1 will certainly be observed; apart from their intrinsic scientific interest observations from the ground and from the WIRE satellite have demonstrated that they show solar-like oscillations at an amplitude sufficiently high to enable very detailed studies. The final selection of the remaining targets will depend on further studies, including ground-based observations to evaluate the fields and the properties of the stars, as well as on modelling to investigate the extent to which the observations may be expected to provide the required information about the stellar properties. Although a definite programme for the start of the mission will evidently be established well before launch, adjustments of the later programme will be possible, in the

### Table 1. Some properties of the Molniya orbit.

| Launch              | SOYUS/FREGAT       |
|---------------------|--------------------|
| Period              | 43080 sec (11.97 hrs) |
| Semi-major axis     | 26560 km           |
| Radius of perigee   | 6900 km (h ≈ 500 km) |
| Radius of apogee    | 46200 km           |
| Eccentricity        | 0.7411             |
| Inclination         | 63.43°             |
| Argument of perigee | ≈270°              |
| Change in ascending node | −0.150°/day       |

Figure 10. The region of the sky that is excluded by Earth light on the main mirror (limb of the Earth 30° away from telescope axis). Also shown are regions where the Moon can get within 40 degrees of the telescope axis. The contours shows the duty cycle for a given position in the sky taking into account the position of the Earth, the right ascension of the orbit perigee and the radiation belts around the Earth. The maximum duty cycle is around 85 % (limited by passage through the radiation belts). The squares show the location of priority 1 targets and the plusses the location of priority 2 targets (cf. Table 2).
Table 2. Possible solar-like targets for the MONS Telescope

| Solar-mass | Low-mass | Higher-mass | Metal-poor | Metal-rich | Fast rotation | Hotter | Total |
|------------|----------|-------------|------------|------------|---------------|--------|-------|
| 1. α Cen A | α Cen B  | η Boo       |            |            |               |        | 4^*   |
|            | β Hyi    | α CMi       |            |            |               |        |       |
| 2. μ Her   | ν And    | ν Ind       | δ Pav      | θ Boo      |               |        | 7     |
|            | β Vir    |             |            |            |               |        |       |
| 2b. ε Eri  | HD 140283|             |            |            |               |        | 2     |
| 3. δ Eri   | ζ Her    | γ Pav       | ψ Cap      | α Tri      |               |        | 11    |
|            | η Cas    |             |            |            |               |        |       |
| 3b. τ Cet  |           |             |            |            |               |        | 9     |
| 70 Oph     |           |             |            |            |               |        |       |
| 36 Oph     |           |             |            |            |               |        |       |

^*Note that α Cen A and B will be observed simultaneously.

light of the information obtained from the first observations. Evidently, information about the general properties of solar-like oscillations obtained with the MOST mission (cf. Matthews, these proceedings) expected to be launched well before Rømer, will also be taken into account.

The stars listed in Table 2 may loosely be characterized as solar-like oscillators. In addition to these, a modest amount of observing time will be assigned to other types of pulsating stars as well as to studies of eclipsing binaries and planet transits.

7. Parallel science

As discussed by Gilmore (these proceedings) space-based photometry offers unique possibilities, for a broad range of astrophysical objects and phenomena, in terms of precision and continuity. Although the Rømer instrumentation is more modest than what will be provided by the Eddington mission discussed by Gilmore, the nearly continuous observations of fairly extended fields, by the Field Monitor and the Star Trackers, allow potentially very valuable studies within a number of areas.

The potential of observations from space of even modest instrumentation was demonstrated by the 5.4-cm star tracker on the otherwise failed WIRE satellite, which has provided valuable data on low-amplitude stellar pulsation, despite the rather unsuitable orbit of WIRE (e.g. Buzasi et al. 2000; Cuypers, these proceedings). The Rømer Star Trackers will have a precision better than 3 mmag in one minute, for all stars brighter than magnitude V = 6. As illustrated in Fig. 8 an even better performance is expected for the Field Monitor. As a result, science with the Star Trackers and the Field Monitor is seen as a high-priority goal by a broad international community, and must be considered as an important part of the mission, in parallel with the science to be carried out with the MONS Main Telescope.

Potential targets for the parallel science include ‘classical’ pulsating stars; for these we expect a substantial increase in the number of modes detected, compared with ground-based results, possibly leading to the identification of a fairly substantial fraction of the modes within the part of the oscillation spectrum, typically a frequency range, where unstable modes are found. As a result we may hope, from the frequency patterns, to be able to determine the nature of the modes observed; this is a prerequisite for the full use of the frequencies for asteroseismology. Our inability so far to identify the modes has been a major impediment to the investigations of stellar interiors from observed frequencies of ‘large-amplitude’ pulsating stars.

In several cases, particularly solar-like oscillations in subgiants, we expect the Star Trackers to be sufficiently sensitive to determine at least the overall properties of the oscillations of the stars. In such cases, Star-Tracker observations can serve as very useful precursors for later observations of a star with the Main Telescope: from the determination of the amplitude and gross frequency characteristics we shall be in a better position to optimize the observing programme to be carried out.

Summed images, in particular from the Field Monitor, have a very interesting potential for studying variations on longer time scales of faint objects. Examples include detection of extra-solar planets through transits, detection of supernova explosions in distant galaxies and the possible detection of smaller objects in our solar system.

We also note that the data from the Star Trackers have very considerable potential for use in outreach activities, such as projects for schools or amateur astronomers.
8. THE MONS SCIENTIFIC COMMUNITY

The MONS project involves a substantial international community, comprising around 150 scientists, taking part both in the preparation of the mission and in the planning of the utilization of the data. This is organized in the MONS Science Consortium. Detailed information about the activities of the MSC can be found on http://astro.ifa.au.dk/MSC. Within the MSC several working groups have been established to deal with specific aspects of the project, such as different types of targets or the ground-based support observations:

- **Solar-like oscillations**: This group deals with stars showing solar-like oscillations, *i.e.*, modes excited stochastically by convection. These are typically stars on or near the main sequence, which will be targets for the MONS Main Telescope.

- **B stars**: This group deals with pulsating B stars, including β Cephei stars, slowly pulsating B stars and Be stars. These will in most cases be observed with the Star Trackers and Field Monitor, but a few may be selected for observation with the Main Telescope.

- **A and F stars**: This group will deal with pulsating A and F stars, including δ Scuti stars and rapidly oscillating Ap stars. They will in most cases be observed with the Star Trackers and Field Monitor, but a few may be selected for observation with the Main Telescope.

- **Planets and eclipsing variables**: This group deals with study of eclipsing binaries and transits of giant planets. These will in most cases be observed with the Star Trackers and Field Monitor, but particularly interesting, predicted, transits could be selected for observation with the Main Telescope.

- **Ground-based support observations**: This group takes care of the ground-based observations required for the MONS project, including redetermination of stellar parameters, investigations of target fields and follow-up observations of pulsations (*e.g.* to help mode identification).

The primary MONS data analysis will be carried out at the Science Data Centre at the University of Aarhus. Distribution of data and other relevant information, such as results of ground-based support observations and theoretical results, will be organized through the MONS Information System (see http://astro.ifa.au.dk/MIS).

9. SCHEDULE

The Detailed Design Phase of the Römer project was formally started at a kick-off meeting on 2 October 2001. This phase is funded by a grant of 12 MDkr (around 1.5 MEuro) from the original phase of the Danish Small Satellite Programme. Complete funding is being sought at the time of writing through extension of the programme beyond 2001. Assuming that funding is made available at the start of 2002, the Implementation Phase will commence in the middle of 2002, while the Detailed Design Phase will end by a Detailed Design Review at the end of 2002. With this schedule launch is foreseen in the middle of 2005; however, a definite schedule will have to await the establishment of a more precise funding profile.

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