Recent Insights into the Physics of the Sun and Heliosphere:
Highlights from SOHO and Other Space Missions
IAU Symposium, Vol. 203, 2001
P. Brekke, B. Fleck, and J. B. Gurman eds.

Recent Progress in Asteroseismology

J. Christensen-Dalsgaard

Teoretisk Astrofysik Center, Danmarks Grundforskningsfond, and
Institut for Fysik og Astronomi, Aarhus Universitet,
DK 8000 Aarhus C, Denmark

Abstract. Asteroseismology, the study of stellar interiors on the basis of observations of multi-mode stellar oscillations, extends over a large part of the Hertzsprung-Russell diagram. The recently discovered EC14026 stars promise information about the properties of stars on the horizontal branch. Solar-like oscillations excited stochastically by convection have been tentatively identified in a few cases. Promising examples are giant stars, where the expected amplitudes may make ground-based observations of the oscillations relatively straightforward. Major advances can be expected from the upcoming asteroseismic space projects under development or study, including the Eddington mission adopted by ESA as a 'reserve mission' in the recent round of selections.

1. Introduction

As documented elsewhere in these proceedings, dramatic advances have been made in recent years in our knowledge about the structure and dynamics of the solar interior, from helioseismic investigations based on solar oscillation frequencies. Much of this work is based on the excellent data that have been obtained from the helioseismic instruments on SOHO. For distant stars oscillation data are unavoidably much more limited. However, the Sun is just a single, relatively simple star in a rather early stage of its evolution. As a result, it lacks many features found in more massive or more evolved stars; an important example is convective cores, which play a substantial role in the evolution of stars just slightly more massive than the Sun and the physical properties of which are highly uncertain. To approach a more complete understanding of stellar structure and evolution, we need to study a broad range of stars of very varying properties, including composition, mass and evolutionary state. Furthermore, the information obtained from helioseismology does not provide unique constraints on the physics of the solar interior. For example, the inferred error in the modelling of the solar internal sound speed (see Turck-Chièze 2000) might arise from errors in the composition profile, possibly associated with the neglect of mixing, or from errors in the opacities used in the computation; data on other stars, combined with an improved understanding of the physics, might help deciding between these possibilities. Also, a more complete understanding of the excitation of the solar oscillations would be greatly helped by data on pulsations, excited in a similar manner, in other stars.

Fortunately, pulsating stars have been identified in essentially all regions of the Hertzsprung-Russell diagram, covering all stages of stellar evolution from the main sequence to white dwarfs, and a broad range of stellar masses. Although the data in some cases are limited to one or a very few modes of oscillation, in many cases rich spectra of oscillation frequencies have been determined, promising detailed information about the stellar properties. Also, it is likely that further improvements in observing techniques, including observations from space, will lead to detection of oscillations at ever lower amplitude; one might speculate that eventually *all* stars will be observed to be pulsating at some level.

In this short review I can evidently hope only to provide a glimpse of the prospects of such asteroseismic investigations of stellar interiors. Thus I have chosen to concentrate on a few types of stars, where new results have been obtained recently. Other cases might equally well have been considered; an important example is the δ Scuti stars (e.g. Breger & Montgomery 2000).

2. Properties of stellar oscillations

As a background for the following sections, I here provide a very brief overview of the properties of stellar oscillations. More complete treatments can be found, for example, in the reviews by Gough (1993) and Christensen-Dalsgaard & Dziembowski (2000) as well as in the book by Unno et al. (1989).

Two fundamentally different mechanisms are available to excite pulsations in a star: intrinsic overstability of the pulsations and extrinsic forcing of otherwise stable pulsations. In the case of overstability, the star acts as a heat engine, through appropriate phase relations between the heating and compression of the stellar gas. In practice, different parts of the star may act to damp or drive the pulsation. Overstability only results, roughly speaking, when enhancements in opacity are at the right depth beneath the stellar surface (see Cox 1974). Depending on the relevant opacity feature, different regions of overstability arise in the HR diagram: the 'classical' Cepheid instability strip, containing Cepheids, RR Lyrae stars and δ Scuti stars, is the result of an opacity bump coming from the second helium ionization, whereas pulsations in B stars arise from the opacity from iron-group elements. Calculations based on this opacity mechanism are generally quite successful in predicting the regions of instability in the HR diagram; a remaining uncertainty, however, is the effect of convection which in most cases appears to suppress instability for stars cooler than the Cepheid instability strip (e.g. Baker & Gough 1979; Houdek et al. 1999; Houdek 2000). Also, the theory only determines whether a given mode is stable or unstable; very little is known about what determines the actual amplitudes of the modes.

Stable modes of oscillation may be driven by external forcing. There is strong evidence that this is the case in the Sun, stochastic forcing being provided by the vigorous convection near the solar surface which is an efficient source of sound waves. Confirmation of this mechanism has come from statistical analyses of the distribution of solar amplitudes (e.g. Chaplin et al. 1997; Chang & Gough 1998). Unlike for the overstable modes theory provides a prediction of the amplitudes of the stochastically excited modes; hydrodynamical simulations of solar convection have shown that the energy input from convection matches the requirements of the observed solar modes (e.g. Stein & Nordlund

2000ab). Since the driving extends over a broad range of frequencies, so do the predicted, and in the solar case observed, modes; as discussed in Section 4 this potentially simplifies mode identification. Similar oscillations are expected in any star with substantial near-surface convection. Predictions of the expected amplitudes have been made from relatively simple models of the interaction between convection and pulsations (e.g. Christensen-Dalsgaard & Frandsen 1983; Houdek et al. 1999). On this basis Kjeldsen & Bedding (1995) derived scaling relations for the dependence on stellar parameters: the relative luminosity amplitude at wavelength λ is estimated as

$$(\delta L/L)_\lambda = \frac{L/L_\odot (4.7 \pm 0.3)\,\mathrm{ppm}}{(\lambda/550\,\mathrm{nm})(T_{\mathrm{eff}}/5777\,\mathrm{K})^2 (M/M_\odot)} , \qquad (1)$$

where M and L are stellar mass and luminosity, $M_\odot$ and $L_\odot$ are the corresponding quantities for the Sun, and T_{eff} is the effective temperature.

A mode of stellar oscillation is characterized by the degree l and azimuthal order m of the spherical harmonic that describes its geometrical properties, with $|m| \le l$; modes with $l = 0$ are spherically symmetric, or *radial.* Observations of distant stars, where the stellar disk cannot be resolved, are generally sensitive only to low-degree modes. For each (l, m) the star potentially has a a large number of modes characterized by the radial order n. The modes are broadly characterized by the dominant restoring force: for p modes, which have the dominant nature of trapped acoustic waves, this is pressure, whereas for g modes, i.e., internal gravity waves, the restoring force is buoyancy. The p modes have their largest amplitudes near the stellar surface, although low-degree p modes extend to the stellar core; g modes tend to be concentrated in the stellar interior.

Which of these modes are actually excited evidently depends on the physical nature of the mode and the excitation mechanisms. The overstability arises predominantly very near the stellar surface where the properties of the modes are essentially independent of the degree. Thus the selection of unstable modes in a given star is predominantly determined by the frequency; depending on the type of star this may include both p and g modes. Stochastic excitation in principle excites *all* modes of a star; however, the amplitude depends on a balance between the energy input to the mode, which takes place near the stellar surface, and the damping. Since low-frequency p modes and g modes have small amplitude near the surface, compared with the amplitude in the bulk of the star, the resulting amplitudes are very small. Thus, as observed in the Sun, the spectrum is dominated by acoustic modes of fairly high radial order.

The cyclic frequencies ν_{nl} of these acoustic modes approximately satisfy a simple asymptotic relation:

$$\nu_{nl} \sim \Delta\nu (n + l/2 + \epsilon) , \qquad (2)$$

where $\Delta\nu = (2 \int_0^R \mathrm{d}r/c)^{-1}$ is the inverse acoustical travel time across a stellar diameter, R being the surface radius of the star and c the adiabatic sound speed (e.g. Vandakurov 1967; Tassoul 1980). This approximately uniform distribution of frequencies plays a major role in the observational identification of solar-like oscillations. The departure from Eq. (2), quantified by the small separation

$$\delta\nu_{nl} = \nu_{nl} - \nu_{n-1\,l+2} , \qquad (3)$$

measures the properties of the stellar core, and hence the age of the star.

I have so far ignored the dependence of the oscillation frequencies on azimuthal order m; this is in fact valid for spherically symmetric stars. Departures from spherical symmetry introduces an m dependence. The most important effect comes from rotation; for slow rotation the resulting frequencies of p modes approximately satisfy

$$\nu_{nlm} \simeq \nu_{nl0} + \frac{m}{2\pi} \langle \Omega \rangle \, , \tag{4}$$

where $\langle \Omega \rangle$ is a suitable average of the angular velocity Ω (e.g. Gough 1981).

3. EC 14026 stars

This group of stars was identified as pulsating in parallel theoretical (Charpinet et al. 1996) and observational (Kilkenny et al. 1997; Billères et al. 1997) investigations. It consists of hot so-called *horizontal-branch* stars, in the phase of core helium burning, following ignition in a helium flash at the tip of the red-giant branch. Their location at the blue end of the horizontal branch, with effective temperature around 35 000 K, is a result of their having lost most of the original hydrogen envelope. For a recent review, see O'Donoghue et al. (1999).

Since their discovery, around 20 members of this group have been detected. The oscillations are excited through the opacity mechanism operating in the opacity bump coming from iron-group elements, likely enhanced by radiatively driven levitation and settling (Charpinet et al. 1997). They are characterized by rich spectra of oscillation frequencies, potentially allowing detailed investigations in this late and relatively poorly understood phase of evolution.

Most observations of these stars have been carried out in broad-band photometry. However, recently two groups have succeeded in measuring oscillations in radial velocity. Such observations are potentially very important in providing information about the identification (i.e., the degree and possibly azimuthal order) of the modes. O'Toole et al. (2000) observed the star PG 1605+072 and found clear evidence of oscillations in three modes (or groups of modes) in the Balmer lines of hydrogen. The frequencies agreed with those obtained through photometry, with substantially higher frequency resolution, from a multisite campaign by Kilkenny et al. (1999). Interestingly, O'Toole et al. found that for a given mode the radial-velocity amplitudes decreased with increasing order in the Balmer series (i.e., decreasing wavelength). This presumably reflects aspects, so far not understood, of the behaviour of the oscillations in the stellar atmosphere. Jeffery & Pollacco (2000) observed the stars KPD 2109+4401 and PB 8783; in the latter case, five or six modes were identified, again agreeing in frequency with modes observed in photometry; the photometric observations show strong evidence for rotational splitting of most of these modes, indicating that they are nonradial. Further spectroscopic observations, with longer time basis, are required to resolve the modes and obtain more precise information about the amplitude and phase relations, for use in the mode identification. Additional information can also be expected from other properties of the spectral lines; an important example is observation of oscillations in equivalent widths.

The rich spectra of oscillation frequencies potentially strongly constrain the properties of the stars, provided the observed frequencies can be identified with modes of stellar models. Even without further observational information about the degrees of the modes, this may be possible through fits of the frequencies to those of models of varying parameters. A very interesting example was provided by the analysis by Billères et al. (2000) of observations of PG 0016+067. Identification of the modes led to stringent constraints on the parameters of the star, including the mass $M_{\rm H}$ of the hydrogen-rich layer, which was determined as $\log M_{\rm H}/M = -4.50 \pm 0.22$. Also, the surface gravity was obtained with a precision of around 2 per cent. Interestingly, the remaining residuals between the observed and fitted frequencies were substantially larger than the observational errors, indicating errors in the model calculations; one might hope that further analysis of these residuals may indicate how the models should be improved, beyond the assumptions of the original calculation.

4. Solar-like oscillations

Solar-like oscillations may very broadly be defined as modes that are stochastically excited by turbulent convection, as observed in the Sun. As discussed in Section 2, this is expected to give rise predominantly to spectra of p modes of fairly high order. Also, the balance between energy input, damping and the structure of eigenfunctions may be expected to lead, at least in stars not too different from the Sun, to a broad maximum in power, as observed in the Sun. This has been used as an important signature in the search for such oscillations. Furthermore, the broad-band nature of the excitation is likely to cause most or all of the modes in the relevant frequency range to be excited, at least over a sufficiently long observing period (over short periods the stochastic nature of the excitation may cause some of the modes to have unobservably small amplitudes). Combined with the regular frequency structure, characterized by the large and small frequency separations (cf. Eqs 2 and 3), this greatly simplifies the identification of the modes, as was found in the early stages of helioseismology (e.g. Christensen-Dalsgaard & Gough 1981). The principal difficulty of this type of modes is the very small expected amplitudes (cf. Eq. 1), making ground-based observations extremely challenging.

4.1. Stars near the main sequence

Much of the effort towards detecting solar-like oscillations has been concentrated on stars near the main sequence. Early claims were made for α Cen A (e.g. Gelly, Grec & Fossat 1986; Pottasch, Butcher & van Hoesel 1992), with somewhat conflicting results. Evidence for oscillations has been found in η Boo from observations of line intensities (Kjeldsen et al. 1995) but may have been contradicted by radial-velocity observations (Brown et al. 1997). Also, an extensive coordinated campaign with most of the world's largest telescopes (Gilliland et al. 1993) failed to detect oscillations in stars in the open cluster M67, in some cases reaching upper limits well below the prediction in Eq. (1).

A promising case is Procyon (α CMi) where Brown et al. (1991) reported oscillations in radial velocity with approximately the expected dependence on frequency. This early detection has recently been confirmed by Martić et al. (1999), again using radial-velocity observations (see also Martić et al. 2000); a power spectrum of these observations is shown in Figure 1. A careful analysis

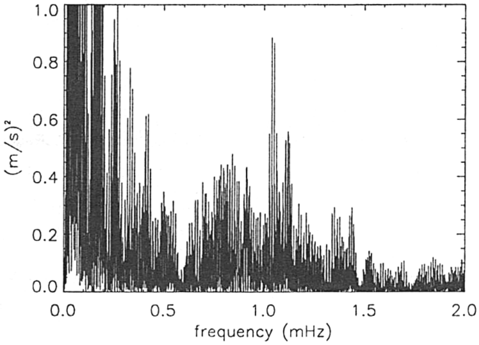

Figure 1. Observed power spectrum of Procyon, based on radial-velocity observations. (From Barban et al. 1999.)

by Barban et al. (1999), comparing the observed spectra with simulated data for models of Procyon, led to a determination of the large separation $\Delta\nu \simeq 56\,\mu$Hz, in good agreement with model predictions. Interestingly, the observed amplitude was only about 1/3 of the predictions, confirming the inference from M67 that Eq. (1) is an overestimate; it should be noted that both Procyon and the stars observed in M67 are somewhat hotter than the Sun.

Evidently, α Cen A remains of very great interest: it is quite similar to the Sun and, being member of a nearby well-studied binary system, its parameters are known quite precisely. Detailed modelling of the α Cen system has recently been carried out by Guenther & Demarque (2000) and Morel et al. (2000). Kjeldsen et al. (1999) carried out extensive observations of line-intensity variations in α Cen A; although hints of oscillations were found, they were only able definitely to determine an upper limit to the oscillations, consistent with Eq. (1). However, very encouraging results have been obtained using the star tracker on the otherwise failed WIRE satellite (see Buzasi 2000). Schou & Buzasi (2001) obtained a convincing detection of oscillations in continuum intensity, with a maximum amplitude of around 6 ppm, roughly consistent with Eq. (1) and a large separation of 106 μHz, again largely consistent with model predictions.

Very recently detection of a power enhancement at the expected frequency was reported by Bedding et al. (2000) from radial-velocity observations of the star β Hyi. This is a subgiant with approximately the same effective temperature as the Sun, while the luminosity is higher by a factor of around 3.5. The resulting power spectrum is shown in Figure 2; there is a very clearly defined enhancement of power around 1 mHz, far exceeding the noise level. This is perhaps the first incontrovertible detection of solar-like oscillations in another star; the amplitude is approximately consistent with Eq. (1).

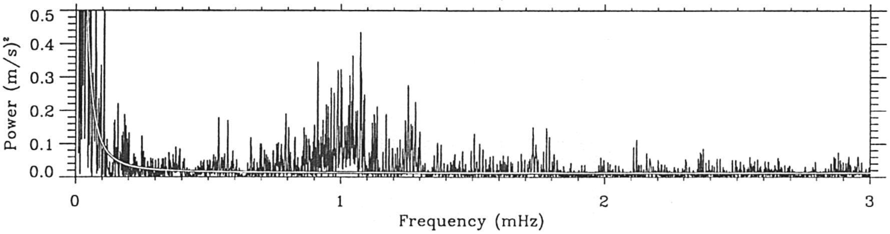

Figure 2. Power spectrum of β Hydri, from radial-velocity observations by Bedding et al. (2000). The white line marks the noise level.

4.2. Subgiants and red giants

Although Eq. (1) is based predominantly on calculations for stars near the main sequence, it indicates that the oscillation amplitudes of solar-like oscillations increase strongly with stellar luminosity. Indeed, Christensen-Dalsgaard & Frandsen (1983) pointed out that red giants could be expected to have quite high amplitudes and speculated that solar-like oscillations might be the cause of at least some cases of semi-regular variability in such stars. Consequently, giants are attractive targets for asteroseismic investigation, with amplitudes such that ground-based studies are relatively straightforward; this might lead to a better understanding of the excitation of solar-like oscillations, as well as provide information about the otherwise rather uncertain properties of the stars, such as their radii. A difficulty, however, is the expected periods of the stars, of order days or longer, requiring extensive observations to resolve the frequency spectra.

Strong evidence has been found for solar-like oscillations in the star Arcturus (e.g. Schmitt, McMillan & Merline 1987; Innis et al. 1988; Merline 1998), including indications of a frequency pattern in accordance with Eq. (2). Also, Edmonds & Gilliland (1996) found variations in K giants in the globular cluster 47 Tuc which were apparently consistent with solar-like pulsations. Recently, based on observations with the WIRE star tracker Buzasi et al. (2000) claimed detection of solar-like oscillations in α Ursa Majoris A, a giant of spectral type K0 III, with an estimated mass, from membership of a binary system, of around $5 M_\odot$. Guenther et al. (2000) analyzed the evolution and oscillation frequencies of this star. They noted that, as a result of the late evolutionary state of the star, the spectra for $l > 0$ were completely dominated by modes behaving like g modes, leading to very dense frequency spectra; thus the only modes that could realistically be identified were the radial modes, which are purely acoustic. Comparing with the observed frequencies, they obtained a tentative identification of some of the modes, although they noted that this was not yet unique. Dziembowski et al. (2000) carried out a more careful analysis of the possible causes of oscillations of α UMa A and concluded that the observed properties of the amplitudes were unlikely to be consistent with solar-like, stochastic excitation. Thus, although red giants remain promising targets for asteroseismology, the current results on α UMa should perhaps be regarded with some caution.

For red supergiants the relevant periods are of order weeks or months, and hence decades of observations are required to resolve the oscillations and study their properties. Fortunately, very extensive sets of data are available from amateur observations, spanning in some cases a century. Although the precision of these mostly visual estimates is not as high as for professional observations, the large amplitudes of the variability allow reliable analysis of the oscillations; also the very extensive base of observations makes it possible to study the statistical properties of the variability. In a very interesting analysis, Mattei et al. (1997) related the *variability* in the oscillation amplitudes to the amplitudes. This isolated the semi-regular variables as a clearly defined class, with a strong correlation between variability and amplitude. Christensen-Dalsgaard et al. (in preparation) argued that this relation corresponded closely to what would result from stochastically excited oscillations where the amplitudes have an exponential distribution, as has indeed been verified for the Sun (e.g. Kumar, Franklin & Goldreich 1988; Chaplin et al. 1997; Chang & Gough 1998). If confirmed by more careful analyses, this would provide extensive data on the excitation of solar-like oscillations over a very broad range of stellar parameters.

5. Future prospects

Recent results on stellar oscillations show a great deal of promise for the development of asteroseismology. In addition to the examples discussed here, extensive data are being obtained on a broad variety of pulsating stars. Particularly striking are the data obtained from comprehensive projects surveying very large numbers of stars, for example in search of gravitational micro-lensing (e.g. Paczyński 2000; see also several reviews in Szabados & Kurtz 2000). Further observations of, for example, δ Scuti stars or the EC 14026 stars will undoubtedly contribute greatly to resolving their complex frequency spectra and hence getting closer to the required identification of the modes. Also, it is very encouraging that strong evidence is being obtained, from ground-based observations, for solar-like oscillations in other stars. Finally, the theoretical studies of mode excitation are providing a steadily improving understanding of the properties of the stochastic excitation of such oscillations. Although the simple models, exemplified by the scaling law given in Eq. (1), apparently overestimate the amplitudes for stars hotter than the Sun, they at least seem consistent with data on stars at solar effective temperature; also, there is no doubt that detailed hydrodynamic simulations will be applied to the study of mode excitation in other stars, as they have been applied with considerable success in the solar case.

The difficulties in the ground-based observations should not be underestimated. In most cases the amplitudes are so small that great care has to be taken to obtain an acceptable signal-to-noise ratio; this is evidently particularly true for solar-like oscillations. Also, the complex frequency spectra (which are of the greatest use for asteroseismology) require very extensive observations, with a high duty cycle; this inevitably demands coordinated observations from several observatories, a challenge in terms of logistics and man-power. For the longer-period oscillations networks of automated telescopes will probably be required.

Although substantial advances may be expected from ground-based observations, these are unlikely to realize the full potential of asteroseismology. In particular, it is entirely unrealistic to reach the required precision and level of continuity to measure detailed oscillation spectra of solar-like stars. Thus it is very encouraging that projects to observe stellar oscillations from space are well on the way. Three of these are relatively small national projects:

- MOST (**M**icrovariability & **O**scillations of **ST**ars), developed by the Canadian Space Agency (e.g. Matthews 1998); this will observe oscillations of a number of stars, including several expected to show solar-like oscillations, with a 15 cm telescope. Launch is expected in 2002. This mission is likely to make the first definite detections of solar-like oscillations in several main-sequence stars.

- COROT (**CO**nvection et la **ROT**ation des intérieurs stellaires), a project of the French Space Agency CNES, with other European contributions (e.g. Baglin et al. 1998); this will make extensive observations of solar-like oscillations in a modest number of stars. Each of these will be observed for 5 months, allowing precise determination of the oscillation frequencies. In addition, COROT will search for planets by observing the decrease in stellar intensity as a planet crosses in front of the star.

- MONS (**M**easuring **O**scillations in **N**earby **S**tars), on the Rømer satellite which is being developed under the Danish Small-Satellite Programme (e.g. Kjeldsen & Bedding 1998). MONS will observe around 20 solar-like stars on or near the main sequence during the planned 2-year mission. The orbit is such that stars in the entire sky will be accessible; in particular, unlike MOST and COROT, MONS will be able to observe the α Cen system.

Although central goals of these missions concern solar-like stars, each mission has the possibility of observing variability in other types of stars. For example, MONS may use the star trackers to study oscillations and other variability in a broad range of stars, with a precision and level of continuity which far exceeds what is available from ground-based observations. Thus we may expect a dramatic increase in data on a broad range of pulsating stars.

Looking beyond these relatively small missions great promise is shown by the Eddington mission (e.g. Favata, Roxburgh & Christensen-Dalsgaard 2000) which has been adopted as a so-called 'reserve mission' in the current programme of ESA. Eddington will use a 1.2 m telescope to observe photometric variability of a large number of stars, with two main scientific goals:

- To carry out asteroseismology on a broad range of stars. Due to the large aperture, solar-like oscillations will be observable for stars in several open clusters, where additional constraints on the stars will greatly aid the use of the oscillation data to study their internal properties. In addition, Eddington will be able to observe oscillations in old, metal-poor stars; this will help testing the modelling of stars in globular clusters and hence the age determination of such clusters, which in some cases has indicated ages in excess of the cosmologically inferred age of the Universe.

- To search for extra-solar planets by observing the luminosity reduction as a planet transits the stellar disk. By observing a very large number of stars

> with high photometric precision it is expected that a substantial number of Earth-like planets will be discovered, including a number in the so-called habitable zone where conditions may be suitable for the development of life; furthermore, the existing evidence on the prevalence of planetary systems with giant planets ensures that a large number of such systems will be studied (see also Deeg et al. 2001).

Eddington will be placed in an orbit near the L_2 point in the Sun-Earth system, where the whole sky can be surveyed with minimal problems from scattered light. A five-year mission is planned; during the first two years a number of fields will be surveyed, for one to two months each, for asteroseismology, whereas the last three years will be dedicated to planet search through continuous observation of a single field. During the latter phase data on stellar pulsations will also be obtained, of particular value for stars with relatively long periods.

Acknowledgments. I am very grateful to the substantial number of authors who have provided results in advance of publication, for use in this review. This work was supported in part by the Danish National Research Foundation through the establishment of the Theoretical Astrophysics Center.

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