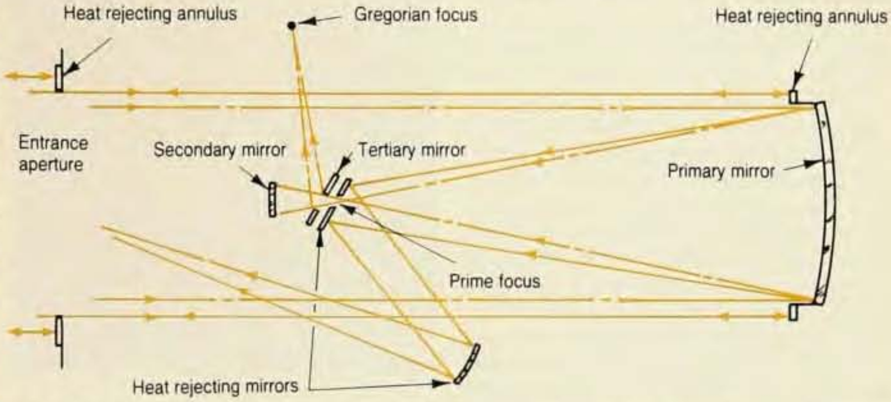
Solar Optical Telescope will orbit on space shuttle



The Solar Optical Telescope will have a folded Gregorian optical design because this provides better heat-rejection capability than does the Cassegrainian configuration more common in night-sky telescopes. The primary mirror focuses the solar image through a hole in a heat-rejection mirror that allows only 3 arc minutes of the Sun to be seen by the concave secondary mirror. A flat tertiary folding mirror directs the image to the off-axis Gregorian focus. The Gregorian optical path is shown as broken colored lines; the heat rejection paths are solid color.

To the naive outsider it seems surprising that solar astronomers complain of being hampered by the inadequate spatial resolution of their telescopes. The Sun is, after all, only eight light minutes away, and most of us don't think of it as possessing small-scale surface features beyond our powers of resolution. Sunspots were studied by Galileo almost four hundred years ago. But in fact, magnetohydrodynamic mechanisms with characteristic scales of 70 km or less appear to be crucial to our understanding of the astrophysics of our nearest star.

The turbulence of the Earth's atmosphere, however, prevents one from resolving solar surface phenomena smaller than about 700 km (one arc second) with any ground-based telescope, except for occasional brief respites of unusually good "seeing." For the past decade, therefore, solar astronomers have been giving serious consideration to the idea of a solar telescope orbiting above the Earth's atmosphere with an aperture diameter of at least a meter—corresponding to a visible-light diffraction limit of about a tenth of an arc second. Besides removing the problem of atmospheric blurring, such an orbiting telescope would be free to look at the ultraviolet part of the solar spectrum, to which our atmosphere is largely opaque.

In 1980, a long-standing study group headed by Richard Dunn (Sacramento Peak Observatory) submitted to NASA its recommendation that a 1.25-meter-diameter, visible–ultraviolet Solar Optical Telescope be built to fly aboard a Space-Shuttle orbiter. This June NASA affirmed its commitment to the SOT project by selecting Perkin–Elmer Corporation as the primary contractor for the detailed design and construction of the telescope. At the same time, Caltech and Lockheed were chosen to build the two principal focal-plane scientific instruments for the initial SOT flights. NASA plans to fly the SOT aboard one of the existing Shuttles for repeated week-long orbital flights beginning in 1988 or 1989.

Ground-based solar telescopes can achieve ⅓-arc-second resolution under unusually favorable atmospheric conditions a few times a year. But such conditions persist for ten or fifteen minutes at best. This is particularly unfortunate for observing solar structures because these are dynamically evolving phenomena of brief duration rather than fixed objects like lunar mountains. To understand the dynamics of the solar plasma and its interaction with the Sun's magnetic fields one really wants hours of continuous observation with a resolution of 0.1 arc second. The corresponding distance—70 km—is regarded as a rather fundamental length for solar surface phenomena because it is the mean free path for photons in the photosphere, the outer layer of the visible Sun.

Since the late 1950s, balloons have occasionally carried solar telescopes aloft. But size limitations have generally kept their diffraction limits to resolutions of no better than ⅓ arc second. Furthermore, balloons don't get high enough to escape the ultraviolet absorption of the atmosphere, and their useful time on any flight is limited to about eight hours. Richard Fisher (NCAR High Altitude Observatory, Boulder), the Telescope Scientist of the SOT project, told us that it would probably cost as much to build a balloon-borne telescope of sufficient size and pointing stability to achieve 0.1-arc-second resolution as to build the orbiting SOT. Rocket-borne telescopes suffer similar limitations of size and pointing stability, and their flight duration is extremely short.

Despite the instrumental limitations, solar astronomers have in the past two decades discovered intriguing small-scale structures that have generally posed more questions than they answer. These observations strongly suggest further detail below the present resolution limits. "Until the late 1950s, many astronomers had a brain fixation that the Sun, and indeed all celestial sources, had no interesting structure smaller than about one arc second," we were told by Robert O'Dell (now at Rice University), Project Scientist of the Space Telescope (PHYSICS TODAY, March 1981, page 59). "But then the flights of the 12-inch, balloon-borne Stratoscope at the end of the decade revealed that the solar granules possess structure at least down to ⅓ arc second." These granules are closely packed, short-lived bright structures (typically a thousand kilometers across) which give the photosphere a cellular appearance. They are believed to indicate the tops of convection cells,

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where columns of rising hot gas emerge from inside the photosphere.

In the early 1970s Dunn and his colleagues at the Sacramento Peak vacuum-tower telescope, which is designated to minimize atmospheric turbulence, discovered "filigree" in the dark intergranular borders, where the cooler gas resubmerges. In brief periods of $\frac{1}{3}$-arc-second seeing, this filigree looks like tiny bright dots, but it is believed that with higher resolution it will show linear structure. It is not yet clear what sort of convective or magnetic mechanism this filigree is manifesting. To understand the granular structure and filigree one will have to observe their evolution at high resolution for extended, continuous periods.

The chromosphere, the solar layer just outside the photosphere that manifests itself in Fraunhofer absorption and emission lines, also exhibits a wealth of small-scale structure that will require better resolution to clarify. The chromosphere is where one finds solar flares, catastrophic energy releases whose mechanism for converting magnetic to thermal energy is not well understood. Data from the x-ray telescope on the 1980–81 orbiting Solar Maximum Mission suggest that the generating mechanism for these flares involves a spatial scale of less than 70 km. The SOT will be well suited, Fisher suggests, to elucidate their origin.

Imaged in the light of the Balmer α line of hydrogen (Hα), the chromosphere looks somewhat like grass growing on a lawn full of large bald spots. The bald spots are "supergranules"—convective cells an order of magnitude larger than the photosphere granules. They are outlined by a grasslike border of "spicules," fine vertical structures whose thickness is smaller than our present limits of resolution. These spicules appear to result from the interaction of the magnetic flux lines and the upward flow of material from the photosphere. The magnetohydrodynamic interaction of the plasma with the magnetic field, Fisher told us, is a central problem of solar physics. One will need to look at the spicules with a resolution three to five times finer than their thickness, he explained. Furthermore, because the lifetimes of chromospheric structures range from tens of minutes to hours, one needs long periods of continuous high-resolution seeing to understand their aggregate behavior.

A dramatic temperature rise—from 1.5×10^4 K to 1.5×10^6 K—takes place in the extremely narrow "transition zone" from the chromosphere to the corona, the outermost layer of the Sun. The high temperature of the corona—more than two hundred times hotter than the photosphere—is one of the major puzzles of solar physics. Recent ultraviolet observations by a Naval

Chromospheric structure is visible in this photograph of the solar surface with an 0.22 Å-bandwidth birefringent filter tuned $+\frac{7}{8}$ Å from the center of the Hα line. Grasslike borders of fine spicules outline supergranular cells tens of thousands of kilometers in diameter. The high-contrast system near the bottom is an active sunspot region. Photograph taken at the Sacramento Peak Observatory.

Research Laboratory group with rocket-borne uv instruments indicate the existence of hitherto unsuspected vertical-flow structures in the chromosphere, with detail smaller than the limits of resolution. Fisher suggests that they may play an important role in coronal heating. But rocket observations last only a few minutes, and ultraviolet emission-line imaging is particularly slow because one must scan with moving spectroscopic slits; the birefringent narrow-band filters that facilitate visible spectroscopic imaging are not available in the ultraviolet.

The Dunn study group, formally referred to as the Facility Definition Team, made its final report to NASA in January 1980. Their report recommended the construction of a 1.25-meter-diameter Gregorian reflecting telescope with wavelength coverage from 115 nanometers in the uv to 1100 nm in the near infrared, with a diffraction-limited resolution of 0.1 arc second at 500 nm in the visible. Infrared observation is given less emphasis because much of it can be done more conveniently with ground-based telescopes. At longer wavelengths resolution is limited by aperture size rather than turbulence, and the atmosphere has generous windows of transparency in the infrared.

The Gregorian telescope design was preferred to the Cassegrainian scheme more common in night-sky telescopes because it facilitates heat shielding. A major problem with solar telescopes is the enormous heat concentration that tends to distort the optics at the secondary mirror and focus. This heat load is a particular problem for the designers of the SOT because the solar image encountered in the orbital environment cannot easily be simulated in the laboratory. Whereas the convex secondary mirror of a conventional Cassegrainian telescope lies before the focus of its primary mirror, the *concave* Gregorian secondary lies beyond it, permitting the placement of a field stop and heat-rejection mirror at the prime focus to protect subsequent optics from concentrated out-of-field solar energy.

The Dunn group recommended that the Gregorian focus be designed to accommodate a visible-light, universal-filter polarimeter employing birefringent crystals, a visible-light spectrograph and a uv spectrograph. In response, NASA has chosen a Lockheed group led by Alan Title to develop the principal photoelectric imaging instrument for the first SOT flights—a visible–ultraviolet, combined filtergraph/spectrograph. Harold Zirin and his colleagues at Caltech have been chosen to develop the principal photographic instrument. The 65-cm solar telescope at the Big Bear Observatory, built by Zirin's group at the Jet Propulsion Laboratory in 1972, has served as something of a prototype for the SOT design.

Pointing stability. The 7-meter-long, 4000-kg SOT will be mounted on a pointing system in the payload bay of the Shuttle orbiter. When the bay doors are opened in orbit, the front end of the telescope will rise like a cannon. A resolution limit of 0.1 arc seconds would be of little use if one could not hold the telescope steady with corresponding precision. One can hold the Shuttle itself stable to within a few minutes of arc by aligning its principal axis along the gravitational field gradient, so that it experiences no torque. For finer pointing stability (two arc seconds), the Shuttle bay will house a double-gimbal pointing system. The final 0.1-arc-second stability must be provided by the telescope itself. This is to be accomplished by a system that provides information about the movement of the solar image to a compensating servomechanism. This feedback system will involve a major design effort on the part of Perkin–Elmer, Fisher suggests. He points out that one is requiring a significantly better pointing stability of this orbiting instrument than one asks of a telescope sitting firmly on a mountain top.

"The Solar Optical Telescope is the cornerstone of our solar physics program for the rest of the decade," we were told by Edmund Reeves, NASA Program Manager for the SOT. Stuart Jordan (Goddard Space Flight Center) NASA's Project Scientist, will organize periodic working-group meetings of potential SOT users to further the implimentation of the project's scientific objectives. Estimated to cost an order of magnitude less than the $750-million Space Telescope, the SOT will be funded as part of the general Shuttle payload-development program; it will not need the separate Congressional approval a budgetary line item would require. The SOT is expected to fly on one of the presently existing Shuttles, but the first launch date, 1988 to 1989, depends on funding levels, Reeves told us. —BMS

High-energy electrons to probe nuclei

Quantum chromodynamics, the gauge field theory that describes strongly interacting particles in terms of their quark constituents and the "colored" gluons that bind them, promises us a definitive theory of the nuclear force. QCD has evolved in the past few years primarily through the rich theoretical and experimental progress of elementary-particle physics at very high energies. Now the nuclear-physics community, whose traditional experimental realm has largely been confined to much lower collision energies, has begun looking to QCD and multi-GeV electron accelerators to provide for the first time an adequate basis for understanding the short-range behavior of nuclear phenomena.

Because many details of QCD are still unclear and nuclei are complex many-body systems, this quest will require an extensive experimental effort. To this end, the Subcommittee on Electromagnetic Interactions of NSAC (the Nuclear Science Advisory Committee) has strong recommended the construction of a variable-energy electron-beam facility capable of high current, continuous (that is, cw rather than pulsed) operation up to 4 GeV. This is the principal recommendation of the Subcommittee's report, *The Role of Electromagnetic Interactions in Nuclear Science*, which was recently approved by NSAC for submission to DOE and NSF. The Subcommittee, headed by Peter Barnes of Carnegie–Mellon University, argued that a 4-GeV machine was needed to investigate the transition region from nucleon–meson to quark–gluon degrees of freedom in nuclei, and to provide sufficiently large momentum transfers to probe nuclei adequately at sub-fermi distances. Electrons are favored as the most suitable probes because they are pointlike particles, impervious to the nuclear force; their electromagnetic interaction with the constituents of nuclear matter is well understood.

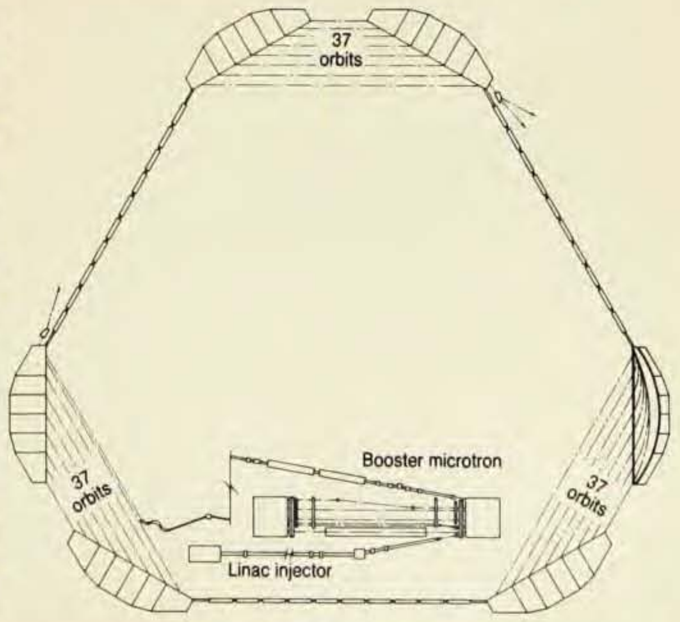
This recommendation goes well beyond an earlier preliminary suggestion contained in NSAC's 1980 *Long Range Plan for Nuclear Science* (PHYSICS TODAY, May 1980, page 20), which called for a cw electron accelerator with a maximum beam energy of only 2 GeV. The stress on cw operation comes from the requirements of coincidence experiments. There already exist pulsed linacs (for example the two-mile-long Stanford Linear Accelerator) that provide nuclear physicists with electron beams of energy higher than 4 GeV. But when all the electrons arrive in microsecond bunches, true coincident signals are swamped by a background of spurious accidental coincidences.

Three groups are preparing to submit proposals to NSAC by the end of the year for the construction of a 4-GeV, high-current, cw electron-beam facility. The Southeastern Universities Research Association, a consortium of 22 universities, has prepared a detailed proposal for a National Electron Accelerator Laboratory to be built at the site of the former NASA Space Radiation Effects Laboratory in Newport News, Virginia. The SURA accelerator would consist of a 2-GeV pulsed linac through which the electron beam would be recirculated once before injection into a pulse-stretcher storage ring—a device for converting the originally pulsed beam into one or more cw beams for experimenters.

Argonne National Laboratory will propose the construction of a 4-GeV "hexatron," a multi-sided, scaled-up generalization of a microtron. (The classic microtron is a small, low-energy, circular electron accelerator, somewhat akin to a cyclotron, first developed almost forty years ago in the Soviet Union.) Electrons will travel repeatedly around a hexagonal loop (hence the name) consisting of three linacs separated by three dispersive bending sections. The Hexatron is designed to fit into the ring building until recently occupied by Argonne's ZGS proton synchrotron.

The Bates Accelerator Laboratory at MIT is examining several alternative options for using the present Bates 400-MeV pulsed linac as the starting point for a 4-GeV cw electron facility. One possibility is to modify the linac for cw operation at reduced energy and build a system of multiple return magnets to recirculate the beam through the linac 15 or 20 times. Alternatively one could extend and modify the Bates linac for higher-energy pulsed operation and use a pulse-stretcher storage ring like the one proposed by SURA to produce continuous electron beams. The group will also propose, as a first step, a 1-GeV cw linac-stretcher facility which could be completed sooner and at lower cost. This would involve a more modest upgrading of the Bates linac and a smaller prototype stretcher ring. Although the technology of rf linacs and electron storage rings is well tried, the only tandem system of pulsed linac and pulse stretcher presently operating is a recently completed 150-MeV facility at Tohoku University in Japan.

Pulse-stretcher rings. RF linacs are



The hexatron, a six-sided microtron design with which the Argonne group proposes to achieve a continuous, high-current beam of 4-GeV electrons. Three 28-meter-long, 35-MeV linacs are interspersed with three pairs of bending magnets. The beam traverses the loop 37 times, each time with a larger radius of curvature in the bending magnets as its energy increases. The 185-MeV injection booster microtron is shown double scale.