THE CATADIOPTRIC REFRACTOR

BY JAMES G. BAKER

Abstract. For the most precise astrometric work it has proved necessary to use only the great refracting telescope, although such an instrument still falls short of perfection. The color curve is so severe that faint companions may become unobservable, or a dependence on spectral type may be introduced. Spectroscopic and spectrographic work are also affected.

The author proposes here a revival of interest in the Schupmann medial telescope, redesigned for the requirements of modern researches, and discusses the pros and cons of such an instrument for astrometric applications.

Introduction. Although there exist many large refracting telescopes that have contributed heavily to astronomical knowledge, astronomers have never yet had the opportunity to use a great refractor completely devoid of color aberration. Such highly specialized researches as astrometry and planetary observations are handicapped by the very marked secondary spectrum inherent in the performance given by the two-element objective of standard crown and flint glass.

The reflecting telescope, though free of color aberration, has never been found to equal the refractor for the above-mentioned kinds of research. In practice, sensitivity to flexure, thermal changes, extra air turbulence in the tube, deterioration of the reflecting film, scattered light, and the rapid loss of quality of the off-axis image all work against permanent precision and reliability. Combinations of mirrors, or mirrors and correcting plates, do away with the coma, but wide separations of individually uncorrected optical parts are not conducive to ultimate precision in astrometry. Improved mounting methods and improved materials may be expected to lead to better performance from reflectors. However, the use of reflectors for astrometry and planetary studies would not appear too promising for some time to come. A more fruitful approach lies in combinations of lenses and mirrors in such wise as to retain the advantages of both, with as few disadvantages as possible.

The makers of the great refractors from long ago have all deplored the apparent impossibility of obtaining a completely flat color curve from combinations of glass types suited to large clear apertures. It is true that both apochromats and semi-apochromats have been manufactured for many years. However, almost invariably the individual elements have strong lens powers which in turn lead to sensitivity to displacement and thermal changes. Also, as a rule, the glass types either cannot be made in large diameter, or else are not sufficiently transparent. Moreover, if a long spectral range is considered that extends into the ultraviolet, even the tertiary spectrum is of such magnitude for the short wave lengths as to prevent adequate focusing of these rays.

As a consequence, none of the great refractors of the world has a color curve appreciably reduced over a certain value which in terms of the focal length is practically a constant. For a visually corrected objective the F and C wave lengths ordinarily are more or less parfocal, and come to a focus approximately 0.0005 times the focal length farther from the objective than the minimum focus in yellow-green. The Yerkes 40-inch refractor has a focal length of approximately 744 inches which leads to a focal error of nearly 10 mm for the F and C wave lengths.[1]

By means of suitable filter and emulsion combinations, astronomers have been able to carry on extremely successful astrometry, but it is obvious that much light is lost from the image and that some enlargement of the image is inevitable if the color band is not narrow. Moreover, red and blue stars may show some variations owing to a change in the effective wave length in combination with filter and emulsion. For spectrographic work only a portion of the starlight can enter the slit, which limits the spectral range that can be adequately covered. For photoelectric work the diaphragm limiting sky light has to be enlarged in order to take in the poorly focused outlying colors, and close doubles can not be accurately measured. In planetary observations the out-of-focus colors tend to lower the contrast of surface detail, which already is low. Laboratory studies at very low contrast indicate that the ultimate resolution depends very critically on the perfection of the telescopic image, even to the extent that residual aberrations well below the Rayleigh limit are still important.[2] Scattered light from reflecting films has about the same effect on contrast. Moreover, the useful field of the average $f/5$ parabolic reflector for planetary purposes is of the order of 1 mm diameter, owing to coma, so that careful centering is necessary. Consequently, it may very well be that a very large refractor yielding a perfect optical image and located at a superior site may in time show us more detail on the planetary surfaces than we have as yet observed. Along such lines, B. Lyot has made a special effort to set up a long-focus refractor on the Pic du Midi for planetary studies.[3] The visual objective of the great equatorial coudé of the Paris Observatory was transferred to the site. Optical flats were added to achieve compactness and to fit an existing mount. The focal length of this great lens is 18.23 meters and the aperture 62 cm.

Because of diffraction the focal depth increases as the square of the focal length for a fixed aperture, whereas the secondary spectrum increases only as the focal length. Therefore, planetary studies undertaken with an ordinary refractor afflicted with secondary spectrum benefit from exceptionally great focal length. However, the usual secondary spectrum is so serious that only prodigious focal lengths can render it unimportant over the full blue-violet to deep red range, where tolerances are set at a fraction of a Rayleigh limit over most of the range. Very probably also, color contrast may be of some importance in observing planetary surfaces where one is working near the limit of vision. The use of color contrast for isolating the coarser details photographically may also be of value for extended spectral ranges. The point is that there are still some unexplored possibilities for a large perfect refractor in an excellent location, not only for planetary studies but for astrometry as well.

During the past 15 years the author has explored many different forms of optical systems in which the secondary spectrum is reduced or eliminated. Certain crystalline materials, such as fluorite, barium fluoride and others in combination with selected glass types allow apochromatic correction. Some plastic materials likewise permit apochromatic combinations. Also, unusual combinations of the ordinary glasses permit either semi- or full apochromatic correction according to the complexity of the design. There are many lens-mirror combinations that have little or no color aberration. Practically all such systems are unsuited to large clear apertures or to astrometry.

While using the Lick 36-inch refractor in 1949, the author found the color curve of the lens to be a serious detriment to his particular task. The problem at hand was to make exploratory observations of stars as close as possible to the limb of Jupiter to see whether atmospheric and relativity shift measurements might not be feasible. The loss of stellar magnitude from the secondary spectrum decreased the number of detectable stars, while with prolonged exposure time, the scattered planetary light from the terrestrial atmosphere and telescope lens caused too much fog. Use of the standard filter-emulsion combination did not improve the star-planet ratio, and overly long exposure times were also not desired.

At this time the author devised the "refractor-corrector," a system reported to the A.A.S., at the Haverford College meetings in December, 1950. The basic idea of this corrector lens stems from the Schupmann medial telescope. The author's particular contribution lies in the recognition that the principle of the Schupmann Mangin can be extended in doublet form to correct the secondary spectrum of even the largest existing refractors.

The refractor-corrector is shown in Figure 1 in schematic form. Briefly, the corrector is a back-

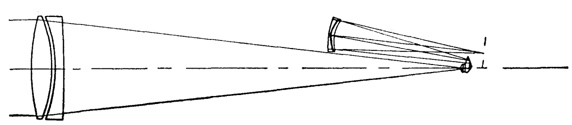

Figure 1. The doublet Mangin refractor-corrector, intended for existing large refractors. The corrector may go either inside of the tube if there is room, or outside if the prism and tailpiece are designed for the purpose. A field mirror may be used instead of the field-lens-prism combination.

surfaced lens-mirror doublet, or compound Mangin mirror, constructed from the same crown and flint combination used for the main objective. In practice, quite different crown and flint pairings are allowable, provided the designer works for the elimination of the known color curve of the objective. An essential feature of the corrector is the use of an achromatic field lens near or at the focal plane of the main objective. The field lens images the main objective onto the Mangin mirror. Thereafter, the lens portion of the Mangin overcomes the lens power of the objective imaged at the Mangin in such a way that for a certain divergent net power of this lens portion, the color aberration disappears. The mirror portion of the Mangin is necessary to reconverge the light to a real focus. Although the Mangin might actually be constructed of separate lens and mirror parts, for simplicity it seems desirable to use a back-surfaced mirror. Thus, the starlight from the main objective comes to its usual first focus with the usual secondary spectrum, passes through the field lens and diverges to form a circular illumination on the Mangin doublet. The Mangin returns the starlight to the second and final focus, this time completely free of secondary spectrum. If the field lens is not achromatic, there will still be a residual of secondary spectrum that can be reduced by some change in glass types. If the field lens is omitted, the secondary spectrum will be only partially corrected and lateral color of the chief rays, which amounts to a change of plate scale with color, will also appear.

The Mangin used at 1:1 re-imaging is free of coma, and with the necessary aspheric figuring, is also free of spherical aberration. By aspheric figuring of both the front and rear surfaces of the Mangin, or by internal design of the cemented elements, one can even remove all traces of the chromatic variation of spherical aberration from the system as a whole. The clear aperture of the Mangin can be assigned over a large range from a Mangin as large as the main objective to a Mangin small relative to the objective; in the latter case the Mangin will be difficult to manufacture and use. Obviously, for large refractors the corrector will be most useful if limited in diameter. For general purposes, a Mangin having a diameter about one-third that of the main objective will prove a good choice. For special purposes, such as in coronagraphic work with small refractors, a full-size Mangin has merit. According to J. H. Rush, High Altitude Observatory at Boulder, Colorado, the planned coronagraph for a 10-foot spar will be adapted from the medial telescope.

The mean field of the Mangin combination is approximately flat. The tangential image surface is concave to the Mangin and the radial surface convex. At aperture ratios of $f/15$ or so, the mathematical field is satisfactorily large. The use of a Mangin is not recommended at smaller aperture ratios unless the field is restricted, but even here, either extensive aspheric figuring will be required, or else a more complicated Mangin must be designed.

The Mangin must be used at about 1:1 re-imaging in the conjugates. One then is faced with the problem of accessibility to the second focal plane. The most direct way is to tilt the Mangin, but as little as possible, consistent with field and performance requirements. One can also use a split field with an on-axis Mangin, or for solar work where light efficiency can be sacrificed, one can employ a beam splitter. In the split-field form the upper semicircular half of the mathematical field is reimaged by the Mangin onto the semicircular lower half of the field at the second focus. The field stop can then be either semicircular or a smaller circular opening within the semicircle. Finally, one can use both the tilt of the Mangin and a partially split field to obtain the largest possible field angle for a given limit on image quality.

The Mangin doublet refractor-corrector, though somewhat awkward to incorporate in existing refractors, can indeed convert these instruments into sharply focusing telescopes of much increased spectral coverage. The loss of light occasioned by the extra transmission and reflections is more than compensated by the focusing action, not to mention the improvement in performance for spectrographic and photoelectric use. Moreover, the corrector can be mounted in such a way that the auxiliary instruments may or may not make use of it as the research requires. It is not the intention here to intimate that the refractor-corrector will automatically cure all ills of the telescope and improve astrometry. The fact is that much careful attention must be given to the design of the corrector mounting. Existing mountings as a rule will be poorly adapted to the addition of such a device. Flexure problems can be overcome through recognition that the field lens images the objective onto the Mangin and that movement of the field lens suffices to remove quite large amounts of flexure if adequate controls are employed. For planetary studies the corrector should prove to be an asset and fairly easy to use. For use with other auxiliary instruments such as a spectrograph or photometer, again careful attention must be given to mounting details. For astrometry it is improbable that a corrector would lead to improved results unless completely adequate attention is given to all phases of the mounting problem, and even here it is a gamble. The reader is referred to the discussion below, where in a related instrument, the problem is given detailed attention.

The Schupmann medial telescope. In 1898 L. Schupmann[4] published a small book under the title "Die Medial-Fernrohre—Eine Neue Konstruktion für Grosse Astronomische Instrumente," containing a detailed account of work initiated as early as 1892 on two types of apochromatic telescopes, the "brachymedial" and the "medial." For the purpose of this paper the brachymedial or simply the brachyt can be forgotten inasmuch as it is ill-suited to astrometric work. The medial, however, has a number of advantages that are not readily apparent to astronomers accustomed to the two-element refractor, and it may be that even for astrometric work an elaborated medial telescope may offer improved results.

It is not clear to the author why Schupmann's medial telescope has been neglected over the years. The few references to Schupmann's original treatment point out the absence of secondary spectrum in the instrument, but do not push the matter. The casual reader may be inclined to think of the medial as an interesting collection of lenses and mirrors, but is not disposed to examine its possibilities critically. The author, however, feels that the medial has been badly neglected and would like to see an awakening of interest in this form of telescope. For one thing alone, the medial contains within its design coronagraphic type optics and yet the final image is apochromatic over an extreme spectral range.

The form of the medial telescope proposed by Schupmann himself is shown in Figure 2. The objective given by Schupmann for his example was to be made of a silicate crown of index 1.516 and ν-value 57.2. This objective was to have a 1 meter aperture and a 15 meter focal length, therefore operating at $f/15$. The objective was to be very weakly biconvex, and designed to be free of coma. For the field lens, Schupmann proposed a right-angle prism of ordinary light crown. The incident face of this prism was to be given a radius of curvature to serve as a field lens for imaging the large objective onto the mirror side of the following Mangin arrangement. For the Mangin compensator, Schupmann preferred a compound form as shown in Figure 2. There is a separated simple negative element through which the light must pass a second time after reflection. Adjacent to this element is a back-surfaced lens-mirror, that is, a Mangin. Both elements were to be made of a light flint glass with index 1.571 and ν-value 43.0. Schupmann's calculations indicated that the residual secondary spectrum had been reduced to about one-eleventh of that of a refractor of the ordinary kind. However, this means that the specific medial worked out by Schupmann as an example would cover the ordinary blue to red visual range quite adequately, but would fail in the violet and ultraviolet according to standards described above.

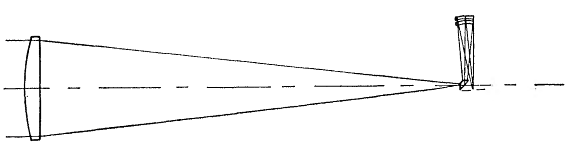

Figure 2. The medial telescope in the specific form proposed by Schupmann. The prism has a single curved face to serve as the field-lens. The Mangin is comprised of a two-element system of light flint glass. The diameter of the Mangin is between 1/6 and 1/12 that of the objective.

Schupmann was aware of this and stated that if the Mangin were made of precisely the same glass as the simple main objective, the secondary spectrum would be exactly zero. His choice of light flint glass for the Mangin was for the purpose of minimizing the lens powers required, and hence for making it easier in his compound Mangin form to find a solution for spherical aberration. Also, the weaker lens powers reduce the sensitivity of the Mangin system to image errors due to tilt. However, for modern purposes the use of a light flint would tend to eliminate a portion of the ultraviolet that can otherwise become accessible.

Schupmann in his example made use of a Mangin system having a diameter approximately $\frac{1}{8}$ that of the objective (11.8 cm). In his discussion of the relative diameter of the Mangin, Schupmann recommended a ratio between 6 and 12, and for the aperture ratio of the telescope objective a range from $f/15$ to $f/12.5$.

The present author sees no vital reason why the diameter of the Mangin compensator should be so extremely small. Even for the Yerkes 40-inch, a Mangin diameter of perhaps 12 inches or so would still be entirely practical. However, such a Mangin could not be mounted so easily at right angles as was Schupmann's own preference, but instead should desirably be back up the telescope tube, just to the side of the main converging cone of rays. The field lens for such a purpose might well be replaced by a field mirror which would be subject to a harmless tilt, or by a more elaborate prism and field lens arrangement, in which two total reflections are required, with little loss of efficiency.

Optically the image aberrations of the Mangin grow rapidly as its size is reduced, owing to the very considerable lens and mirror powers required to correct the large color aberration of the large objective. In effect, if the Mangin is but $\frac{1}{12}$ the diameter of the primary, its own color contribution must be equal longitudinally to that of the primary but with a conjugate distance only $\frac{1}{12}$ as great. The resulting steep curves lead to very large spherical errors and to a large variation of coma with color. Also, the sensitivity to tilt is drastically increased, not to mention that the actual tilt angle must be greater for a given field, and the suitability of the system for precision astronomical work is seriously impaired. Perhaps to some extent, the failure of the Schupmann design to "take hold" with the usual time delay, whereas the equally unorthodox Schmidt camera succeeded, can be ascribed to Schupmann's zeal to overdo the duties of his compensator.

With too small a Mangin it becomes imperative from the point of view of optical design to breakdown the aberrations by means of increased complexity of construction. The compensator shown in Figure 2 thus introduces six more glass-air surfaces and a mirror reflection. Extra light is lost, and the ghost images for some purposes might be troublesome. Also, Schupmann found it necessary to use light flint for the Mangin system in order to reduce the lens powers, and hence the aberrations, with consequent ill effect on the residual secondary spectrum. Now, optical design problems are practically always a matter of compromise, and Schupmann carried through in almost rigorous detail an investigation of what appeared at the time to be most desirable.

Research needs are ever changing, and what is really needed now is flexibility of choice, according to the application. The important thing is not to copy Schupmann's specific examples but to recognize his use of a basic principle of the correction of the secondary spectrum that can be used in far more complicated optical systems. The doublet Mangin corrector introduced by the author for the existing large two-element refractors is a case in point, which in turn can undergo where necessary a considerable variation in application. As pointed out earlier, the Mangin can sometimes be as large as the objective it is correcting, as for coronagraphic work where a simple objective must be used to form a real focus at an occulting disc before further compensation is possible. For small instruments the full size Mangin results in little or no aspheric figuring and permits a substantial tilt without harm.

If the aperture ratio of the telescope is kept between $f/15$ and $f/25$ and if the Mangin diameter is of the order of $\frac{1}{3}$ that of the objective, it becomes feasible to use a simple Mangin, that is, a single back-surfaced element, figured on either or both sides to remove spherical aberration. This aspheric Mangin, once achieved, introduces only two air-glass surfaces and the reflection. Moreover, though light flint glass might still be employed to lessen the lens curve and the aspheric figuring, it is perfectly feasible under these less severe conditions to use exactly the same glass type as for the main objective and therefore to remove the secondary spectrum altogether. Such a telescope then can be used from perhaps 3300 A to 20,000 A according to the transmission of the glass. One can make visual settings in full confidence that ultraviolet or infrared spectrographic or photoelectric observations are in sharp focus on an identifiable object or portion thereof. For solar work in particular, with the main objective used as a coronagraph, one can achieve a drastic reduction in scattered light and obtain spectra of very small solar detail over a very wide spectral range.

A Schupmann medial telescope of a fully practical nature is shown in Figure 3. A 16-inch

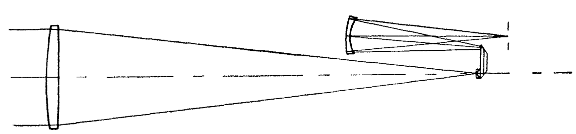

Figure 3. The simplified form of Schupmann medial telescope adopted for the Harvard 16-inch apochromat. The large prism takes the beam outside of the tailpiece to clear the existing mounting. The field lens is cemented to the prism face. The front lens surface of the Mangin is strongly aspheric. The back surface is to be figured slightly to a toroidal shape to eliminate the axial astigmatism.

telescope of this form is nearing completion at Harvard Observatory, through initiation by the solar group and in particular by Richard Dunn and James Gagan. Gagan has made all of the optical parts in the Amateur Telescope Makers' area at the Observatory. Dunn has guided the project throughout, has designed and supervised the construction of the metal parts, and will be using the telescope for his researches on the sun. Intended originally for use in Cambridge as a replacement for the historic and still excellent 15-inch refractor, the 16-inch Schupmann will be mounted in New Mexico on the 26-foot coronagraphic spar. The special prism with two reflecting faces is of the type described by the author at the Haverford meeting, except that for mounting purposes on the 15-inch tube, the prism for the 16-inch replacement has a relatively great light path. The glass is of excellent quality and for solar purposes, there should be no difficulty.

An 8-inch Schupmann telescope was completed in 1952 by Chester Cook of the Boston Amateur Telescope Makers, who carried through the entire project on his own. The expectation of a color-free image has been fully realized, and this 8-inch telescope as well as the later 16-inch version have been very instructive to the author in pursuing the optimum compromises in such systems.

There are many detailed optical considerations in the design of a tilted Mangin system of peak performance. Discussion of such details properly belongs to a later contribution that will summarize very extensive investigations of the optical problem as such. The author's purpose here is to describe the merits of the medial-type telescope for modern researches in astrometry. Applications of the medial to planetary studies, solar observations and general use are obvious and need no further comment at this time.

The medial telescope in astrometry. The author may be in serious error in supposing that the medial can be used for parallax and double-star measurements similar to those researches described by van de Kamp.[5] However, there is no harm in trying, even if the results turn out to be negative, because the medial has many other uses that would justify the construction of a large instrument. The author has no direct experience in such matters and it is largely through the possible availability of a large medial telescope to be described below that his interest in hoped-for improvements in parallax and double-star measurements has been aroused.

The experienced astronomer may feel inclined to condemn the medial because of its wide separations of optical parts, which seemingly lead to flexure problems of extraordinary complexity, which in turn would make astrometry difficult, if not impossible. However, the author feels that such troubles are more apparent than real.

If, contrary to Schupmann's simple field lens, one uses a precision achromatized field lens of top objective quality, and if one images the first nodal point of the main objective precisely onto the vertex of the mirror side of the Mangin by means of this precision field lens, then optically the objective and Mangin are coincident much more closely than if adjacent to one another physically. The same cannot be said of the two-element refractor, ordinarily used for astrometry. In the customary case the flint is indeed separated from the crown and there can be variations in the astrometric field caused by flexure of either element, or by bad centering with respect to one another. In the precision medial now proposed by the author there can be no such centering troubles, if indeed the requisite imaging is accomplished and checked by a Foucault test within the telescope tube. The arrangement should be to have a small artificial star not at the nodal point but shifted to the second surface of the main objective, or in the air just below this surface. The field lens will form an image of this artificial star in the air just beyond the vertex of the mirror side of the Mangin, and a small clear spot can be left at dead center of the mirror for the purpose. When the field lens is properly adjusted, a graying Foucault test will have the main objective and Mangin optically combined in x, y, and z coordinates, irrespective of flexure, and thermal changes of the system. The precision of this adjustment will depend on the quality of the mounting, which must be maximized. If adequate controls are provided for the adjustment of the field lens, and if gradients in flexure and temperature are not too great during the short exposures contemplated, then optical alignment of the highest quality can quite simply be achieved by micrometric adjustment of the field lens. The adjustment even takes into account in a natural way any refractivity of the air in the tube caused by convection and stratification. The author maintains that this adjustment can be accomplished without undue difficulty to a precision not ordinarily achieved in the standard two-element mounting, and in addition one can maintain a constant check on the alignment of his instrument.

There is still the problem of squaring-on of objective and field lens. With the field lens adjusted as described above, a chief ray incident on the first nodal point of the objective will emerge from the second nodal point and will be imaged by the achromatic field lens sharply onto the vertex of the mirror side of the Mangin. Hereafter, any tilt of the objective permitted by the otherwise rigid cell and tube will affect the direction of the chief ray to only a very small angular displacement indeed. The author believes the circumstances are superior to those encountered for the standard two-element mount where the nodal points of the two elements taken separately are displaced. In addition, the simple objective of the medial is precisely corrected for coma, so that the off-axis rays are not affected by first-order tilts to a high degree of accuracy. Finally, the simple element of the medial is much weaker optically than the separate crown or flint members of the standard doublet. A given amount of flexure or lack of squaring-on produces materially smaller angular displacements of the chief rays over the field. There is less center-to-edge variation in thickness and the single element of the medial can be made thicker at the start if deemed advisable.

The Mangin corrector must either be tilted, or used with a split field-stop, or both. One can object that tilting the Mangin will certainly ruin the astrometric quality of the instrument. The author does not believe so, although experience may prove otherwise. To a high degree of approximation, if the Mangin thickness is not excessive and the tilt kept small, the chief rays pass through simply a plane-parallel plate of glass, undergoing reflection at the back surface. If one pays exact attention to the course of the chief rays in passing through the tilted Mangin, the mirror side can be ruled out because the chief rays intersect at the vertex. The lens side finds the incident and emergent chief ray displaced, but complete elliptical symmetry is maintained. The only effect, and it is likely to be a very small one, will be to introduce an azimuthal term in plate scale that is characteristic of the instrument, and no worse than allowances for tangential distortion or plate tilt itself. The exact tilt of the Mangin can be kept under surveillance by another internal Foucault arrangement similar to that employed for the field lens.

In so far as astrometry is concerned, the author feels that the most serious attention must be paid to the behavior of the field lens rather than to the objective portions of the telescope. The angular direction of the chief rays will depend on the power of the field lens, which may change with flexure and temperature. The problem is quite similar to the need of thermostatic control of the deviation of prisms in a spectrograph, and the author feels that the field lens might similarly be carefully controlled by a thermostat. The change in scale produced by a change in field-lens power is similar to the changes in scale ordinarily allowed for in reduction, caused by real changes in the focal length and/or focal setting at a prime focus. What might actually cause trouble are second-order effects. However, one notes that the star images will remain sharp even if the field-lens power changes slightly, and that radial symmetry of the field will be maintained. Thermal gradients within the field lens remain as the most probable source of significant astrometric error. However, as in the atmosphere itself, proper exposure times and a number of plates can overcome errors that are not systematic. Thermal waves within the field lens progress back and forth, and with proper thermostatic control can be minimized. The field lens will radiate to its surroundings, so that the thermostat must be set only as slightly as possible above the ambient temperature in the near vicinity of the lens, and the tube might well be insulated in this region.

Ideally, the field lens should be fully apochromatic of itself, as well as spherically corrected. A quartz field mirror of extra thickness in a rigid mount would serve astrometrical considerations well. Best results would be obtained if the field lens or mirror is not exactly at the focus of the effective wave length being used, but appreciably displaced. The pencil of light passing through the field lens or reflecting from a field mirror from a single star might then be perhaps a centimeter in diameter, or more. In this way, vagaries of dust and scratches can be minimized.

One of the objectionable features of the medial at present is the need to make the Mangin out of optical glass with an accompanying sensitivity to thermal changes. Mangins up to 14 inches diameter can now be made of optical fused quartz, but such a Mangin combined with ordinary crown for the objective leaves an appreciable residual of secondary spectrum. The present alternative for the Mangin is thermostatic control or insulation of the mounting so as to prevent unacceptable errors of figure. The consideration is particularly important if the tube is exposed to solar heat.

The tilt of the Mangin introduces some astigmatism at the center of the field. For example, the 16-inch Schupmann at Harvard will require several fringes of toroidal figuring of the Mangin on the mirror side to eliminate this astigmatism. Toroidal figuring ought not to be too difficult if restricted to such small magnitude. The author in the past has had occasion to make a parabolic cylindrical mirror, with the straight line portion modified into a cubical parabola. The departure of the twisted surface from the cylindrical surface amounted to about 18 waves. The method of surface contouring employed for that task should make a toroidal figuring effort feasible, though ordinary knife-edge testing should be good enough.

Schupmann pointed out that the main objective could be tilted slightly to eliminate this axial astigmatism and worked out the theory of the effect. If the objective is coma-free, then certainly such a tilt can be employed harmlessly. One higher-order difficulty is that the astigmatism of the Mangin is partly of lens and partly of mirror in origin, whereas the compensating astigmatism of the objective is altogether of lens nature. Hence, there is a minor tendency for chromatic astigmatism, but the error at $f/15$ is well within the Rayleigh limit over a wide spectral range. The author prefers toroidal figuring to tilt of the objective, and this preference is all the stronger where astrometry is concerned.

A proposed elaborated medial telescope. The author has been so convinced that the medial telescope has a place in modern astronomy that in the fall of 1951, he procured a 30-inch blank of Schott BK-7 of highest quality to start a project expected to culminate in a valuable research instrument. At first, quite an ordinary Schupmann was contemplated, more or less identical with the 16-inch described above. However, requirements for a field of view large enough to handle the sun or moon with field to spare, with a uniform image quality on a flat plate as well, led to elaboration of the medial optics. The flatness of field was maintained by correction of the Petzval sum, which for the usual Schupmann medial is strongly negative, and astigmatism was eliminated by position, bending and power of the field lenses. Finally, a reimaging small lens was introduced for the purpose of increasing the equivalent focal length for a moderate tube length, and for finding an easy means for eliminating the astigmatism of the tilted Mangin, if needed. Figure 4 shows a cross-section of the proposed instrument. At the present writing the detailed optical design of the untilted system has been finished. The mathematical image quality is entirely satisfactory over a field about 20 per cent larger than the sun's diameter. Over the central part of the field, the image quality on a flat image surface is well within the Rayleigh limit over the ultraviolet to infrared range. The equivalent focal length of the system is 1194 inches, which will make this proposed telescope superior to all other refractors in this respect. The clear aperture is to be 29.0 inches. The actual full size photographic plate is to be 12 × 12 inches, although practically all research plates will be 5 × 7 inches.

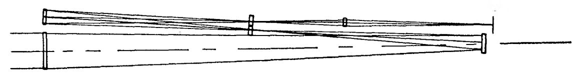

Figure 4. The optical layout for the proposed 29-inch medial apochromat. There are three real focal planes, of which the last is corrected for longitudinal and lateral color, spherical aberration, coma and flatness of field. The equivalent focal length is about 1194 inches but the overall length is only 360 inches. The optical flat is of fused quartz. The small last element is of optical fused quartz to withstand the heating effect of sunlight, which at this small element will have a surface brightness 68 times greater than at the main objective. The tube will probably be filled with helium between the main objective and the small last element.

There has been some prospect that the 29-inch telescope can be mounted on the side of the existing 26-foot spar on Sacramento Peak. Here at an elevation of about 9000 feet in latitude 33°, one has a chance that the seeing will be good enough to justify the aperture. The 26-foot spar is extremely rugged as mountings go, and has a calculated flexure of only 0.001 inch in its entire length after compensation. The apochromatic telescope will be fairly rugged itself. Any residual flexure will be removable by adjustment of the field lenses prior to the taking of research photographs that require special attention of this kind. It is hoped that by the time a decision has to be made on whether the telescope is actually to be built for Sacramento Peak, more detailed information will be at hand from prolonged use of the 16-inch apochromat to be used there. There would be little purpose in adding a 29-inch to the mountain if a year's observation with the 16-inch proves the seeing to be inadequate. However, the optical parts for the 29-inch are going forward in confidence that ultimately a mounting in an adequate place will be made available.

The optical parts for so large a telescope cannot be rushed, particularly since every effort is to be made to ensure near perfection in the entire instrument. A description written by the late Lyot shows the pains to which one must go if perfection is sought in a large refractor,[6] and undoubtedly much tedious effort lies ahead. In the interim while plans are going ahead to make this telescope an actuality, the author has been selecting optical glass for the smaller parts from existing stockpiles here and abroad. The glass companies have cooperated in sending through glass blanks already selected by their own laboratories as being best for the purpose. Some of these blanks have been ground and polished for close optical inspection, and more will undergo the process. The two blanks at hand for the Mangin seem to withstand the most critical knife-edge test and either would be satisfactory. There are no observable bubbles, seed or striae in either blank. Moreover, the 30-inch blank itself has only a very few and very small bubbles, and no striae. Very probably, the 30-inch disc is adequate for coronagraphic work if the polishing should prove good enough. There is a possibility that if a definite project is set up for this instrument, still another 30-inch blank of interferometric and guaranteed quality will be purchased from the Schott Company in order to leave no stone unturned in the attempt to get a really top quality instrument.

Figure 4 shows that an optical flat is necessary in the converging beam to fold up the system for mounting on a 26-foot spar. The use of the flat is to be deplored and interferes totally with use of the apochromat at this time as a coronagraphic telescope. There seems to be no alternative, short of making up a new mounting and building of the general size of the Lick 36-inch refractor. Prospects for such an undertaking are naturally poor, and the uncertainties great enough to recommend against the requisite expenditures. Perhaps later, if research needs warrant the effort, the instrument can be remounted or replaced by another one on its own straight mounting at a still better site. The 29-inch shown in Figure 4 is good for a great deal of work, and is justified, even with the optical flat in the train. The flat itself is of fused quartz. The blank has been procured from England, and optical work has already been started.

Also for this same telescope, a 30-inch Pyrex blank has been procured. This blank will be made into a top quality test flat to be used by auto-collimation with the apochromat. The flat is to be a permanent part of the telescope and will accompany the instrument to the mountain or wherever it may go. The flat is to be mounted in a suitable cell that can be fastened to the telescope for optical checking at any time. The author believes that in this way, a constant watch can be maintained on the quality of the telescope independent of atmospheric seeing troubles. The flat will also be indispensable to the proper figuring and alignment of the entire system.

The optical details of the system would become very burdensome on the reader if pursued too far. However, it should be mentioned that the second field lens will be adjustable in the same way as the first, and will image an artificial star at the center of the small lens onto the same knife-edge test fixture at the vertex of the Mangin. In this way, the alignment of all parts will be under constant control by the observer in a painless way. The Foucault test is to be "piped" by a simple periscopic train of 3-inch objectives from the Mangin to the observer at the focal plane. The observer, while looking into the Foucault eyepiece, will be able to adjust both field lenses by remote control in three coordinates over a micrometric range prior to opening the shutter. The guiding will be accomplished by means of microscopes off the edge of the field and by a double-slide plate holder arrangement. The 5×7 inch plates in particular can be carefully guided on selected centers because of the availability of a fairly large field of view all around this size plate with star images formed by a 29-inch aperture. Economy prevents adding rotational guiding, though this might be desirable for prolonged exposures.

It should be stated that this instrument is not being constructed primarily for astrometric use, but for solar studies and possible planetary studies. Its use in astrometry will be on an experimental basis for some time, and will in effect be a by-product. The use of the telescope for solar observation will require a helium-filled tube for best results and this is being planned. Use of the helium may also reduce the astrometric night errors through elimination of stratification in the long tube. Whether there will be an astrometric gain remains to be seen. The author must take the view that whether or not the instrument proves usable in astrometry, we shall at least find out how close it can come.

The author requests the indulgence of the reader for presenting a telescope on paper before prospects for its existence are definite. However, nothing tried is nothing gained, and the telescope is taking form in a certain number of excellent pieces of optical glass. The completion of the project, if supported by adequate research funds