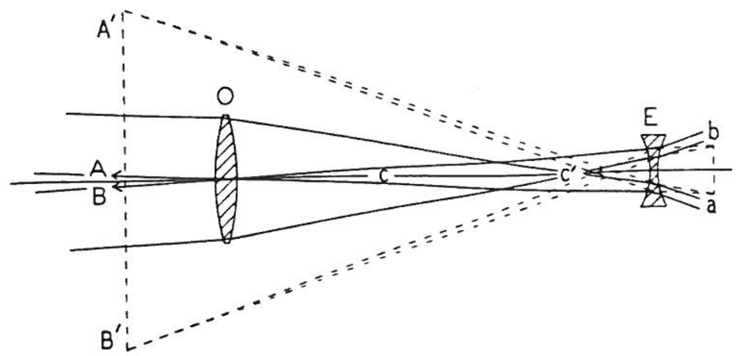


Fig. 2. Image formation in the Galilean (erecting) telescope.

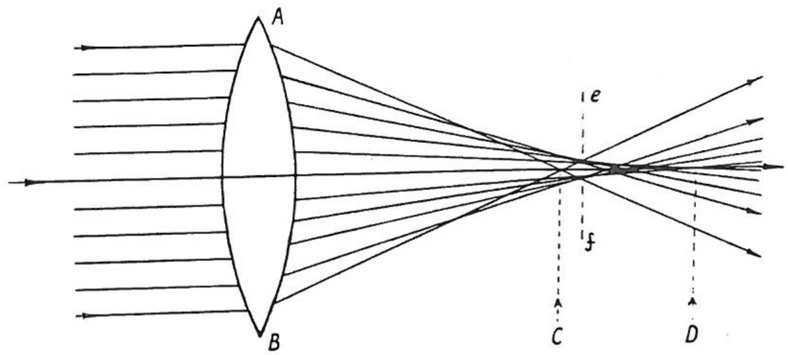


Fig. 18—Spherical aberration

AB Biconvex lens
C Focus for rays incident on marginal zone of lens
D Focus for rays incident on axial zone of lens
CD This distance is the longitudinal spherical aberration
ef The position of the circle of least confusion

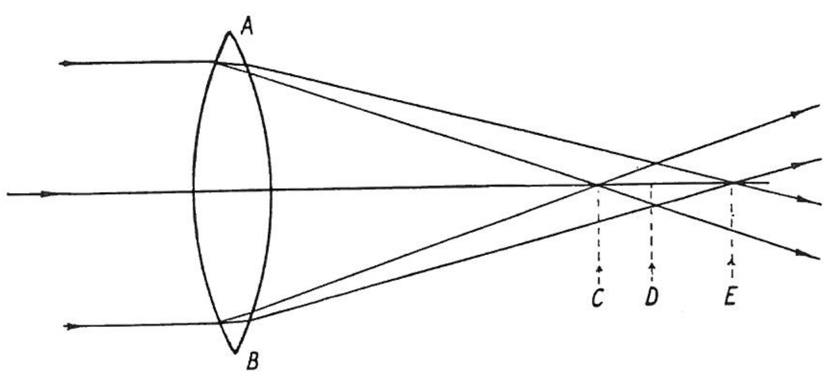


Fig. 19—Chromatic aberration

AB Biconvex lens receiving parallel rays of white light
C Focus for blue rays
D Focus for yellow rays
E Focus for red rays

Optical tests of Galileo's lenses

Vincenzo Greco, Giuseppe Molesini and Franco Quercioli

The science museum in Florence has two telescopes and a single lens attributed to Galileo. Tests conducted with modern interferometric equipment show that Galileo was able to obtain nearly perfect optical quality.

ACCORDING to biographies, Galileo is supposed to have made several telescopes, purchasing some lenses and polishing others himself, yet only the optical apparatus now in Florence, collected and handed down by the Medici family[1], appears to have survived. The authenticity of the telescope tubes seems certain, but some doubts remain about the lenses, apart from the single lens, which was used in the discovery of the Medici stars.

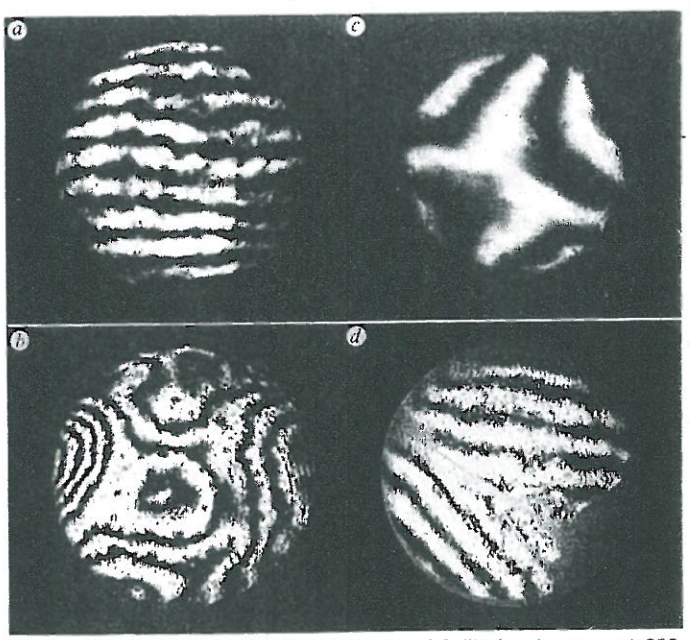
The Medici collection was examined in 1923[2,3], but we have now taken the telescopes apart and tested them with state-of-the-art optical equipment. Analysis of the optical quality of Galileo's lenses is of interest for understanding both the development of optical technology and the observational capabilities of early astronomers. Before Galileo's time, observations were made with the naked eye, for which the resolution is about 1 arc minute. Lenses were used only as eyeglasses or as magnifying lenses, for which applications the poor glass purity and optical figure then feasible were nevertheless adequate.

We have examined Galileo's optics with modern methods. We call the telescopes I (paper coated, longer tube) and II (leather coated, shorter tube). Their optical configuration is based on a positive objective and a negative eyepiece with a common focus. The table summarizes the measurements of the geometry and the first-order optical parameters. The focal lengths are measured in the centre of the visible spectrum (550 nm). From the lens geometries and focal lengths, we calculate that the refractive index of the glasses is 1.51 – 1.55. The relative apertures of the objectives are *f*/51 for telescope I, *f*/61 for telescope II and *f*/45 for the single lens. The magnification of the telescopes is 14 for I and 21 for II.

OPTICAL DATA OF GALILEO'S LENSES

	Front radius	Back radius	Central thickness	Full diameter	Aperture diameter	Focal length
Objective I	2,700	950	2.5	51	26	1,330
Eyepiece I	plane	48.5(*)	3.0	26	11	−94.0
Objective II	535(*)	Plane	2.0	37	16	980
Eyepiece II	51.5(*)	51.5(*)	1.8	22	16	−47.5
Single lens	940	12,000	4.0	58	38	1.710

Asterisks, data from ref. 3. Dimensions are in mm.



Fizeau fringe patterns of the optical elements of Galileo's telescopes at 633 nm. The fringe maps show the deviation of the wavefront from a sphere or a plane. For reference, a diffraction-limited wavefront produces no fringes, or straight and equally spaced fringes if some tilt is added. *a*, Double-pass interferogram of objective I, folded with a reference mirror. Deviations from straight fringes are of the order of half a pitch, meaning a departure from the ideal wavefront of the order of a quarter of a wavelength. *b*. Reflection interferogram of the concave surface of eyepiece I. Fringes are highly irregular. *c*, Reflection interferogram of the plane surface of objective II. The quadrant fringes show astigmatism. *d*, Double-pass interferogram of the single lens.

We used a 633-nm digital phase-shift Fizeau interferometer to study the regularity of the optical surfaces and the wavefront distortion in transmission. Typical fringe patterns are shown in the figure. As far as regularity is concerned, the quality of the objective lenses is far better than the quality of the eyepieces. But because the used diameter per field angle at the eyepiece is much smaller than the clear aperture of the objective, the effect of the lower quality of the eyepieces is negligible. It is surprising that the plane surfaces of eyepiece I and objective II (*c* in the figure) are really plane to a fraction of a wave, although flatness of these surfaces is not required in terms of image quality. (Polishing a surface to such flatness is not trivial even for today's crown glasses.)

A further observation comes from the appearance of the concave surface of eyepiece I (*b*). In addition to the interference fringes, a pattern of ring shadows appears, as if the surface had traces of a turning process. The wavefront distortion of objective I is very small (*a*). The best quality belongs to the single lens, which can be considered as nearly diffraction-limited (*d*). According to the Rayleigh criterion, its resolution at 633 nm is of the order of 3 arcseconds. Of course, the optical performance of the telescopes is degraded for several reasons, mainly chromatic aberration. Computer simulations taking dispersion into account lead to estimates of only 10–20 arcseconds resolution over the visible spectrum.

Altogether, our tests of the lenses (made 350 years after Galileo's death) show that they are polished to a good spherical shape, and the presence of proper apertures on the objectives also shows Galileo's awareness of the need to tune the optical performance. As a result, although affected by intrinsic chromatic aberration, at single wavelength the telescopes are nearly diffraction-limited, that is, optically perfect. □

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2. Abetti, G. *L'Universo*, **4**, 685–692 (1923).
3. Ronchi, V. *L'Universo*, **4**, 791–804 (1923).