HOW TO BUILD A TELESCOPE

如何制作望远镜

THE FIRST TELESCOPE

第一台望远镜

As I said, you can build this first simple instrument without difficulty while allowing you to learn the structure and operation of telescopes in general. Although it is simple, it can reveal the craters of the Moon and the satellites of Jupiter. It is also very useful for demonstrating lens aberrations. You really need to build this telescope as a necessary step towards understanding the solutions employed in the second and improved telescope model. In the section "From Lenses to Optical Instruments", you saw how a telescope works; here I simply remind you that the objective lens produces an image of the object observed, and this image is magnified by the eyepiece.

当你了解的望远镜的一般结构和操作方法之后，你也能够毫不费力地做出这台简单的仪器。虽然它很简陋，但是它能够向你展示出月球表面的大坑和木星的卫星，同时它还有助于你理解透镜像差。制作和使用这个望远镜有助于你深入理解随后即将说明的改进的望远镜的结构模型。在“从透镜到光学仪器”这个部分，你将了解到望远镜是如何工作的；这里，我简要地说明一下望远镜的工作原理：物镜对被观测的物体进行成像，然后这个像被目镜放大。

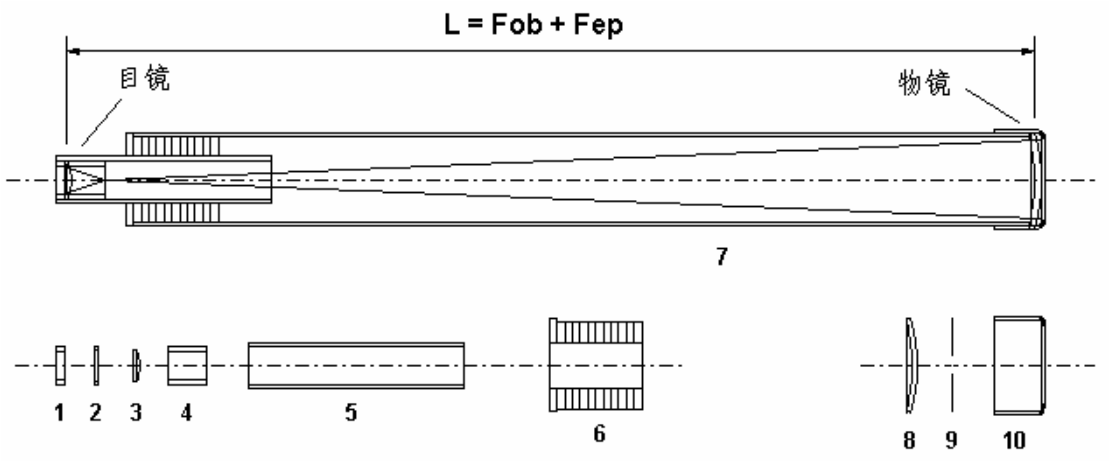


图2 – 第一台望远镜的结构

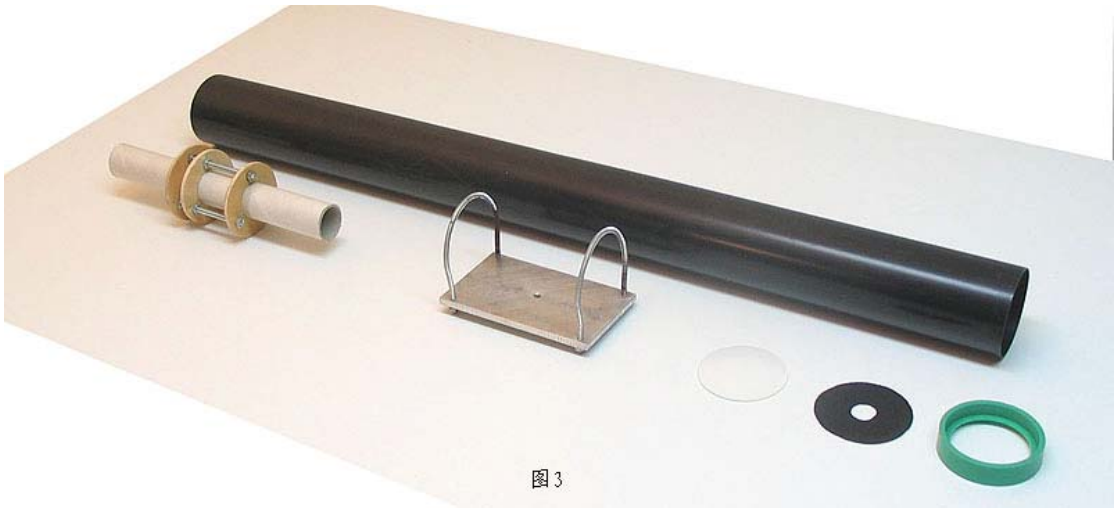


图3

Figures 2 and 3 show our first telescope, which is made using easy-to-find materials. The components of this instruments are:

图2和图3展示出了我们的第一台望远镜,它使用易于找到的材料进行制作。这台仪器使用的零件如下:

1 - ring to secure the eyepiece lens from behind
1 – 从目镜后方保护目镜的环形垫片

2 - ring for centering the eyepiece lens
2 – 将目镜固定在中间的环形垫片

3 - eyepiece: lens with focal length of 20-50 mm. You can buy one in an optical or photographic shop, or you can get one free by using the lens of a disposable camera.
3 – 目镜: 焦距为 20-50mm 的凸透镜。可以从光学或者摄影店买到，或者是使用一个照相机的镜头。

4 - ring to secure the eyepiece lens from the front
4 – 从目镜前方保护目镜的圆筒

5 - a cardboard tube for the eyepiece. You can use the tube from a roll of plastic food wrap or paper towels. You can also use short sections of this tube to make rings 1, 2, and 4 which you need to hold the eyepiece lens in place
5 – 使用卡纸做成的圆筒，用来固定目镜。可以使用大小合适的塑料的食品包装盒或者是纸巾中心的圆筒。你可以用这个圆筒较细的部分来制作零件 1，2 和 4。

6 - coupling between the eyepiece tube and the main tube. This is a hollow cylinder with an outer diameter that fits snugly into the end of the main tube and an inner diameter that provides a snug but movable fit to the outside of

the eyepiece tube. You can make the coupling using several plywood disks glued together or using a polystyrene cylinder with a hole bored through it. If you use polystyrene, you will need to add an opaque covering at each end.
6－目镜和主镜筒的连接部分。这是一个外径大小刚好能够放入主镜筒，内径大小刚好可以把目镜筒放入而又能够灵活移动的空心圆柱。可以用胶水将大小相同的几个中央有孔的圆盘粘接到一起或者是使用聚苯乙烯塑料做成的中央有圆洞的塑料来制作。当你使用聚苯乙烯塑料时，要记得在圆柱的两个端面贴上不透光的纸或者其它材料。

7 - main tube. Use a cardboard or plastic tube about as long as the focal length of the objective lens and with an outside diameter of 50-60 mm about. Suitable sources include map mailing tubes and core tubes for carpets, drawing paper, or wrapping paper.
7 － 主镜筒。使用一段外径 50-60mm 的卡纸筒或者是塑料管来制作，圆筒的长度大约等于物镜的焦距。合适的材料有邮寄地图的圆筒，或者是地毯，绘图纸，包装纸中心的圆筒。

8 - objective lens. You can use a common eyeglass lens with a focal length of 500-1000 mm. You can buy it in a optical shop. Ask the optician to reduce the lens diameter in order to fit it precisely into the tube cap
8－物镜。可以使用焦距为 500 到 1000mm 的老花镜的镜片。可以从眼镜店买到。可以让眼镜商将镜片磨小以便安装到你的主镜筒中。

9 - diaphragm. Cut it from a black card, then open a hole of about 15 mm in diameter in the center of the disk
9－光阑。从黑色的卡片上剪下，然后在中央开一个直径 15mm 的圆孔。

10 - Cap of the tube. If you buy a tube for drawing sheets, you should have a cap which will be useful for retaining the objective and the diaphragm. Otherwise, you can made it with a disk of cardboard. Make a series of radial cuts around the edge of the disk to make a set of tabs, Moisten the tabs; then place the tube cap on one end of the principal tube and bend the tabs around the outside of the tube. Glue the tabs together where they overlap, but be careful not to glue the cap to the principal tube yet. When the glue is dry, slip the cap off and cut in the cap a hole a few mm less in diameter than the outside diameter of principal tube.
10 － 镜筒盖。如果你使用一个图纸管作为你的主镜筒，你将有一个盖子用来方便地固定主镜和光阑。如果没有的话，也可以自己用卡纸自己做。在圆形卡纸周围沿直径方向刻出许多小槽，做出许多小的突出部分，将它们打湿，把卡纸片放到主镜筒头部，将突出部分折到主镜筒上，然后使用胶水将卡制片边缘突出部分重叠到一起的部分用胶水粘到一起，这个过程要小心，不要将胶水弄到主镜筒上，以免将这个镜筒盖粘到主镜筒上。胶水干了以后将镜筒盖取下，在中央开一个直径略小于主镜筒的圆孔。

The distance between objective and eyepiece lenses must be equal to the sum of their focal lengths. The eyepiece tube must stick out a few centimeters so you can move it to focus the telescope. Make the length of the principal tube short enough to allow you to grip the protruding part of the eyepiece tube with your fingers as you adjust the focus.

物镜和目镜之间的距离应该等于它们的焦距之和。目镜必须露出一小段，以便于你能够前后移动它使望远镜聚焦。主镜筒的长度应该合适，使你在前后移动目镜调焦的时候始终能够抓到目镜突出的部分。

The eyepiece tube must slide smoothly in its channel, but it should not be loose enough to fall out if you hold the telescope vertically. Paint the inside of the tubes with black opaque paint (matte finish) or India ink . Secure the cap of the main tube to keep it from pulling away from the tube.

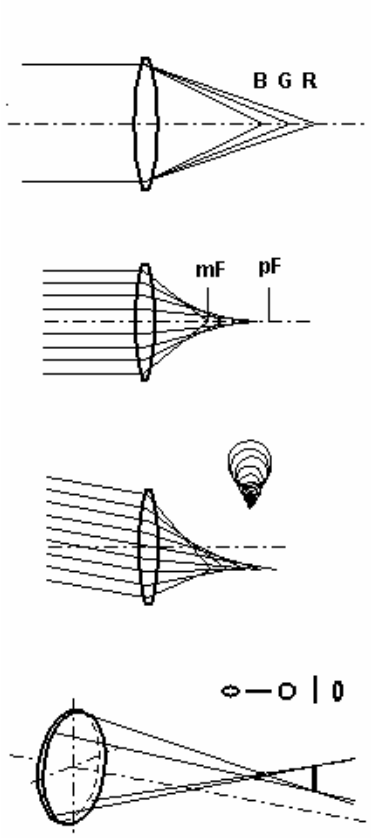
目镜的圆筒要能够在固定它的圆筒中平滑移动，但是又不能太松以免望远镜在垂直状态下时目镜掉出来。在主镜筒内壁刷上黑色颜料或者是墨汁。保护好镜筒盖防止它被从圆筒中推出。

LENS ABERRATIONS

透镜像差

The first telescope will give you a good feel for lens aberrations (fig. 4). In this simple instrument, chromatic aberration is the most conspicuous. The aberrations can be greatly reduced by means of careful lens design. As it is not possible to limit all kinds of aberrations using only a single lens, objectives and eyepieces are created using multiple lenses. By selecting different types of glass for the various lenses and using appropriate surface curvatures and distances between lenses, it is possible to control in a satisfactory manner the aberration of the system. In general, the success of an objective or an eyepiece in correcting aberrations depends on the number of lenses used to make it.

第一架望远镜有助于你对透镜像差（图 5）有一个直观的认识。在这台简单的仪器中色差是最明显的。通过精心的设计能够减少透镜的像差，但是使用单片透镜的设计不可能消除所有的像差，实际中物镜和目镜都是采用多片透镜制造的。通过使用不同型号的玻璃和合适的透镜表面形状能够将透镜的像差控制在比较满意的水平。总的来说，目镜或物镜对像差的纠正程度和它使用的透镜数量有关。



色差

白光由多种色光组成。当白光通过透镜时，不同颜色的光线被弯折的程度不同。如图所示，蓝色光的焦点要比红色光更靠近透镜。如果不纠正色差，通过你的望远镜看到的物体的边缘看起来就是一边是蓝色，另一边是橙色。

球差

考虑远处一个在透镜光轴上的发光物体和它在透镜另一侧成的像。球差导致远离光轴的光线和靠近光轴的光线的会聚点的位置不同。

彗差

与球差类似，彗差影响不在透镜光轴上的物体的成像。在一台有彗差的光学仪器上，一个亮点的像由一系列的中心不重合逐渐缩小的圆盘组成，看起来就像彗星。

散光

导致一个圆点在焦平面以外的投影变成椭圆。当成像平面在焦平面的另一侧时，椭圆光斑的长轴旋转90度。

场曲

透镜的焦平面不是理想的平面而是一个曲面。

失真

远离透镜光轴的焦距的不一致会产生失真，导致直线的像变成曲线。常见的失真有有枕形失真和桶形失真。

图5 主要光学像差

For the second telescope, shown in figure 12, we use an achromatic objective, made up of two lenses of different shapes, one converging and the other diverging. Sometimes they are glued together by means of Canada Balsam or a synthetic resin (cemented doublet), other times they are kept separated (air-spaced doublet). These two lenses have different indices of refraction, one high (Flint glass), and the other low (Crown glass). Hence, the chromatic aberrations of the two lenses act in opposite senses, and tend to cancel each other out, thus producing a much more distinct image than a single lens could achieve.

在第二个望远镜（图 12）里，我们使用一个消色差物镜，它由两片不同形状的透镜组成，一片是凸透镜，另外一片是凹透镜。有些情况下它们是使用 Canada Balsam 或者是合成树脂胶合在一起，有些情况下，他们是分离的。这两片透镜使用的光学玻璃具有不同的折射率，一个透镜玻璃的折射率高（铅玻璃），另外一片透镜使用玻璃的折射率较低（冕牌玻璃）。因此这两个透镜的色差指向相反的方向，趋向相互抵消，从而能够获得比单片透镜清晰很多的成像。

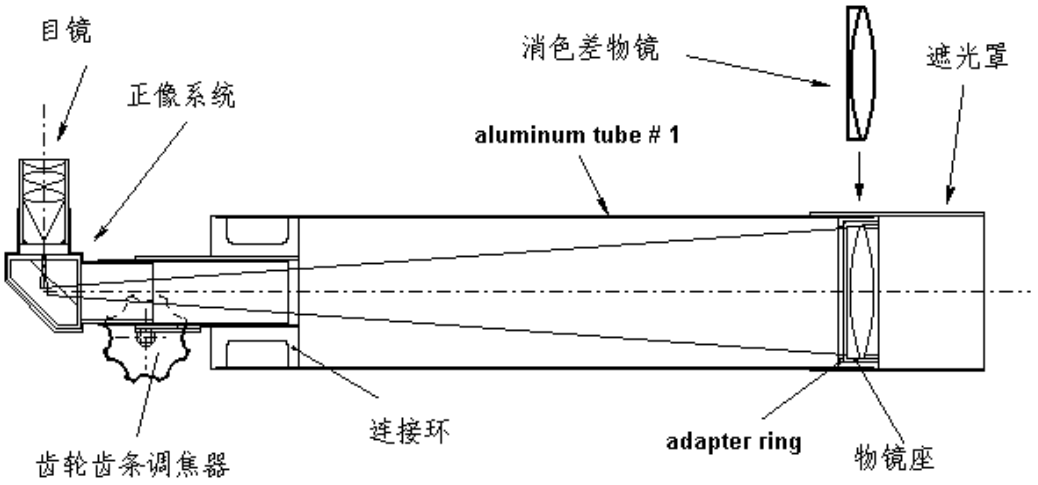


图12 – 消色差望远镜

Usually, these objectives are constructed to reduce other types of aberration as well. Obviously, achromatic objectives vary in quality. In some of them, it is still possible to perceive a residual chromatic aberration, or the images they produce are well focused in the center only, or they produce a pincushion or barrel distortion. Figure 3 describes the main optical aberrations.

通常情况下，这些透镜在制造的时候也会考虑消除其它像差。显然，消色差物镜的质量有优劣之分。有些消色差物镜，能够感觉到残余色差的存在，或是只是中心成像聚焦良好，或者有桶形失真。图 3 说明了了主要的光学像差。

EYEPIECES

目镜

In our first telescope, we used a simple magnifying glass as the eyepiece. Also eyepieces made up of a single lens are affected by several aberrations, particularly chromatic, and with a single lens it is not possible to eliminate them. In the early 1700s, Huygens showed that he could eliminate chromatic aberration in an eyepiece using a system of two lenses. Since then, many

eyepiece models have been designed to obtain better and better corrections, a wider field corner, etc. However, eyepieces always retain the same basic function of magnifying the real image formed by the objective. The main parameters that characterize an eyepiece are the following:

在我们的第一台望远镜中，我们简单地使用一个放大镜作为它的目镜。目镜使用单个透镜也会产生一系列的像差，特别是色差，使用单个透镜无法抑制透镜的色差。在 17 世纪早期，惠更斯展示了一种使用两片透镜减少色差的目镜光学系统。此后，各种形式的目镜被设计出来用于获得更好的像差纠正、更大的视场等。不管是使用哪一种形式，目镜的功能都是放大物镜对观测物体成的实像。衡量一个目镜的主要参数如下表所示。

Parameter 参数	Defines 定义
MODEL 目镜形式	Aberration corrections 目镜形式
FOCAL 焦距	Focal lengths combine to determine the magnification power of the telescope 目镜的等效焦距用来确定望远镜的放大倍率
FIELD 视场	Determines how wide the image appears to the eye. A wider field makes the telescope more comfortable to use 确定眼睛能够看到的范围大小，大视场的目镜使望远镜的使用更为舒适
EYE RELIEF or EYE DISTANCE 出瞳距离	Indicates the proper distance from the eye to the eyepiece lens 观察时眼睛到目镜透镜的合适距离
DIAMETER 直径	Indicates the outside diameter of the eyepiece tube. Most eyepieces have diameters of either ~24 mm or ~32 mm 指出目镜筒的外径，大部分的目镜直径是~24mm 或者~32mm

In addition to those shown in figure 6, other types of eyepieces can be made by using more lenses. Such fancy lenses are made for special purposes, and they are usually expensive.

除了图 6 中列出的这些目镜以外，其他形式的目镜可以使用更多的透镜。这类目镜一般是为了特殊的使用场合制造，通常情况下它们都很贵。

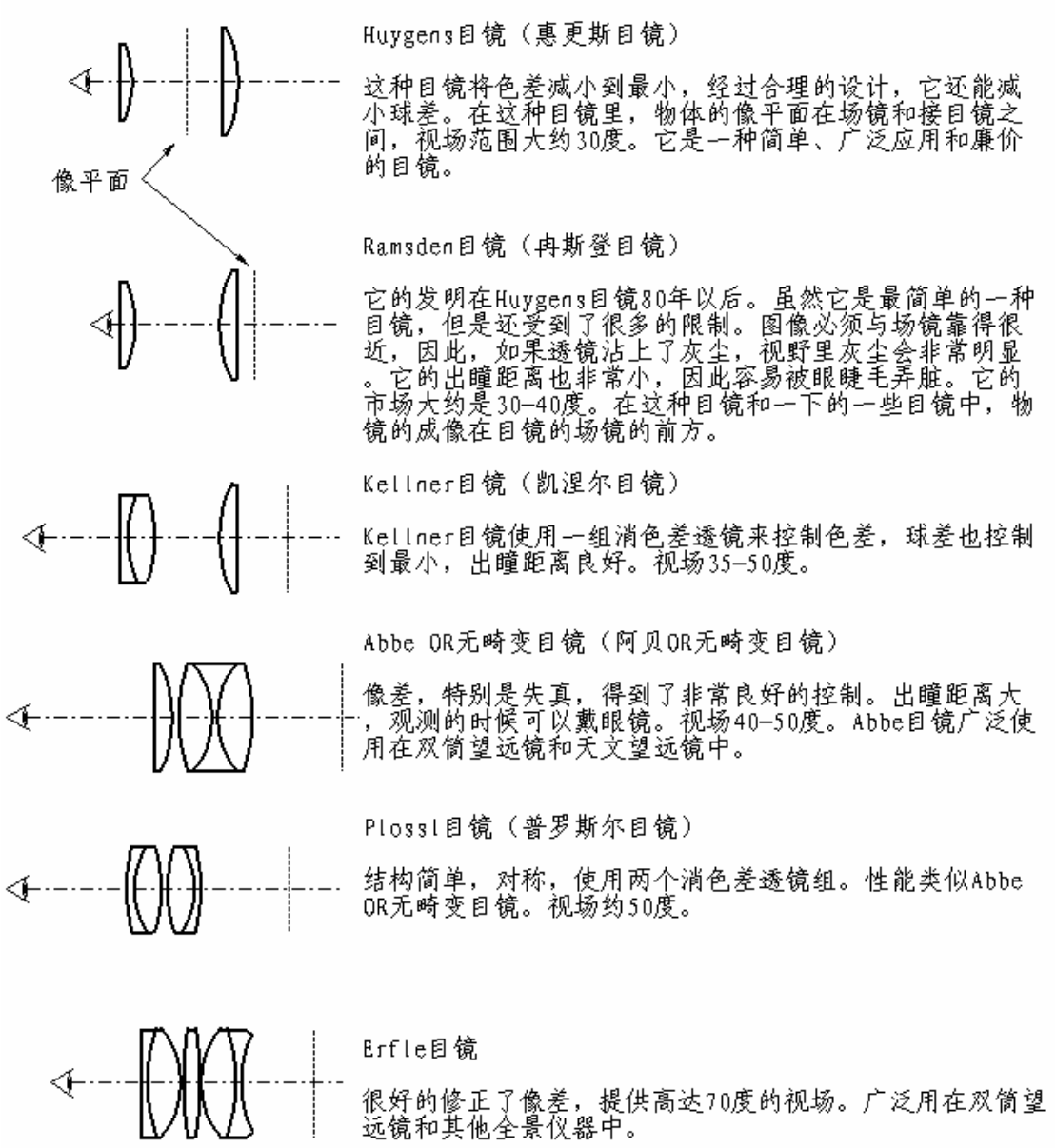


图6 常见的目镜

PRODUCING AN UPRIGHT IMAGE

产生正像

With the first telescope you built, images were inverted, and in the section "From Lenses to Optical Instruments" I explained why. But astronomers don't really care whether they see star images "straight up" or "upside down." In fact, with the exception of the Sun, all stars are so distant that not even with the most powerful telescopes has anyone ever seen their disks. They appear

to us always as points of light, and to see a point of light upright or overturned does not make any difference. However, many people would like to use their telescopes for terrestrial observations, in which case "right side up" does make a difference.

使用第一台望远镜看到的像是倒立的，在“从透镜到光学仪器”这个部分我已经解释了原因。天文学家并不真正在意看到的像是“正立”或者“颠倒”的。事实上，除了太阳和太阳系较大的天体以外，因为其它恒星距离我们太远，即使是使用最强大的望远镜，也没有人能够看到其它它们的圆面。它们对于我们来说就是一个点光源，对于一个点来说，正立和倒立没有任何区别。然而，有很多人还使用他们的望远镜对观看地面上的物体，这个时候是不是正立的成像就是一个非常重要的问题了。

Several different methods allows you to erecting images without significantly degrading their quality. Figures 7, 8, 9, 10, 11 show the main erecting systems. These optical devices are sold with a case and tubes for connecting them with the eyepieces and the focusing systems.

可以通过多种方法在不严重降低成像质量的情况下获得正像。图 7，8，9，10，11 说明了常见的正像系统。这些光学器件一般安装在一个外壳中出售，外壳用来将它们与调焦系统和目镜连接。

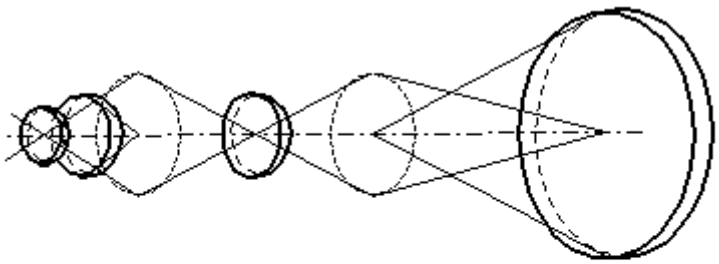


图7 – 正像镜是一个消色差透镜，放在目镜和物镜之间，用于反转物镜的倒立成像。这样的正像系统的缺点是增加了望远镜的长度。优点是可以使用它来改变望远镜的放大倍率。

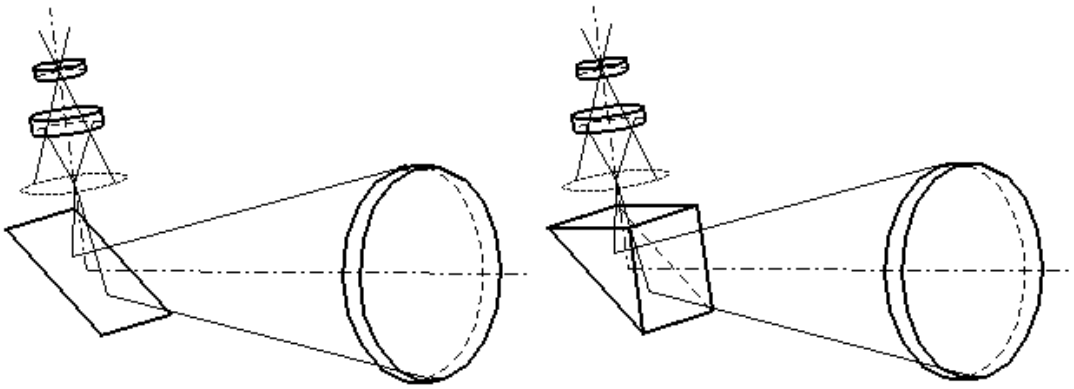


图8 – 使用平面镜或者是棱镜能够是物体在上下方向上成正像，但是物体的像是左右颠倒的。

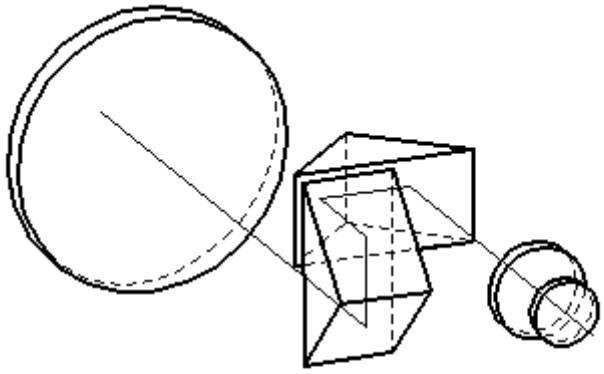


图9 – 两个棱镜，在双筒望远镜里的位置，使望远镜成完全正像，同时也缩短了镜筒的总长度。

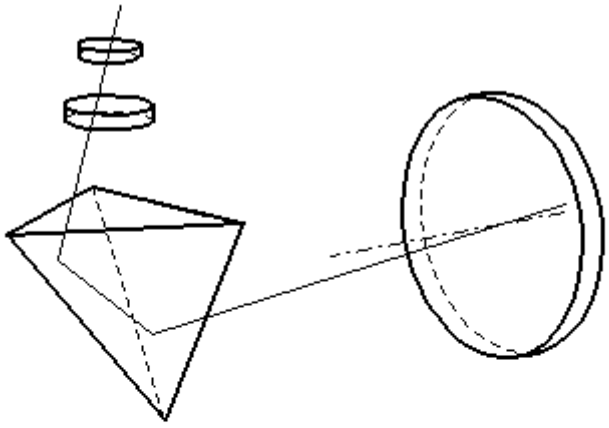


图10 – 屋脊棱镜或者阿米西棱镜正像系统，物像在四面体棱镜内反射两次，光线与入射方向成直角。图像完全正像。90度弯折的光路使得观测天顶附近的天体很容易。Bevels on the prism have been omitted for clarity.

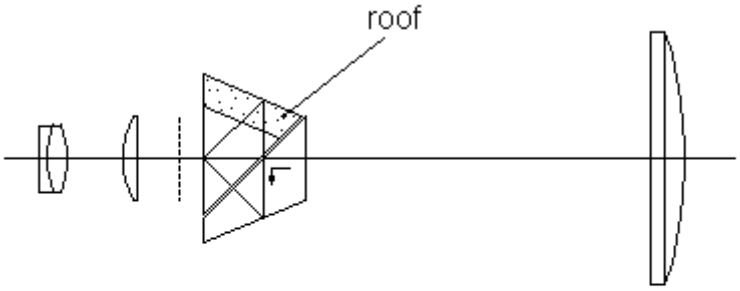


图11 – 使用两片棱镜的正像系统，其中一片棱镜是屋脊棱镜。出射光轴和入射光轴方向同轴，这种正像系统用在mini双筒望远镜中。

AN ACHROMATIC TELESCOPE

消色差望远镜

During the construction of this second telescope (fig. 10), we will use improved technology and manufacturing methods to achieve better performance than we could get from our simple first telescope. To build this instrument, you will need:

第二台望远镜的制造过程中，我们将使用改进的技术和制造方法来获得更好

的性能。为了制造这台仪器，我们需要:

- an achromatic objective with a diameter between 40 and 100 mm, and with a focal length between 600 and 1200 mm
- 一个直径 40 到 100mm，焦距 600 到 1200mm 的消色差物镜

- an eyepiece with a focal length between 20 and 40 mm. Any model show in figure 4 is good, with the exception of the Ramsden eyepiece
- 焦距 20 到 40mm 的目镜。除 Ramsden 目镜外，图 4 中列出的其它形式的目镜都符合要求。

- a rack and pinion focusing system. It is made up of two tubes sliding one into the other. The inner one is moved by a rack and pinion couple
- 一个齿条齿轮调焦器。它由两个圆筒构成，一个圆筒插在另外一个圆筒中，内部的圆筒使用齿轮和齿条来进行移动。

- an image erecting system (see figures 7-11)
- 一个正像系统（见图 7-11）

- the main tube in aluminum #1. Buy it with a length equal to the objective focal length. Its inside diameter must be greater than the diameter of the objective mounting bracket
- 使用 aluminum #1 的主镜筒。买一段长度等于物镜长度的铝管。铝管的内径要大于物镜的安装托架

- adapter ring in black plastic or aluminum
- 塑料或者是铝制的黑色适配环

- coupling ring in black plastic or aluminum
- 塑料或者是铝制的黑色连接环

- light shade tube
- 遮光管（罩）

You can buy objective, eyepiece, erecting and focusing systems from suppliers who advertise in astronomy magazines, or you can ask an amateur astronomy club for advice. In any case, make sure to choose diameters for your components such that they will fit each other; otherwise, you will need to fabricate fitting rings. You will have to make the principal mechanical parts with a lathe. If you do not have one, you can go to a machine shop. Since the parts are all quite simple, you shouldn't need to spend a lot. In any case, ask for a cost estimate. Students of high schools, technical colleges and universities can often get access to their school laboratories. If you want to get your own machine tools, you can find commercial Chinese-made lathes

that are available for less than a thousand dollars. For the same price, you can buy also a small used lathe.

你可以从天文杂志上推荐的供应商那里得到需要的物镜，目镜，正像系统和调焦器，你也可以咨询业余天文俱乐部得到建议。在任何情况下，选择合适直径的零件保证他们能够相互配合；不然你需要制作适配环。主要的机械结构需要使用机床来进行加工。如果你没有机床，你可以到一个机械商店去加工。因为零件都比较简单，你不需要花太多的钱。任何情况下，首先取得一个估计预算。中学，技校或者是大学的学生通常能够在学校的实验室进行加工。如果你想拥有一个自己的机械加工设备，可以在市场上找到一些中国制造的机床，使用不到 1000 美元就能够买到，同样价格也可以买到使用不太多的旧机床。

RESOLVING POWER AND MAGNIFICATION POWER

分辨能力和放大倍率

The magnification of the telescope (M) is given by the ratio between the objective and eyepiece focal lengths: M = Fob/Fep. You cannot simply magnify at will, seeing more and more details. The maximum magnification you can reach with a telescope is limited by the diameter of the objective. The larger the diameter of the objective, the closer are the points it is able to distinguish as separated.

望远镜的放大倍率由物镜焦距和目镜焦距的比率给出 M= Fob/Fep。你不能将你观察的物体放大到任意的倍率，一台望远镜能够达到的最大放大倍率由物镜的直径限制。物镜的直径越大，望远镜能够分开靠得越近的点。

The resolving power (RP) of a corrected objective, expressed in seconds of arc, is given by RP" = 120/D where D is the diameter of the objective in millimeters. The human eye has an RP of about 60". Hence, the maximum magnification you can obtain from an objective (MM) is given by the ratio between the RP of the eye and that of the objective: MM = RPeye / RPob.

经过校正的物镜的分辨能力（RP）使用弧秒来表述。RP = 120"/D，其中 D 是物镜直径的毫米数。人眼的分辨能力大约是 60"。使用一个物镜能够获得的最大有效放大倍率可以由人眼的分辨能力和物镜的分辨能力的比率给出：MM = RPeye/RPob。

For instance, an achromatic objective with a diameter of 80 mm has an RP of 120 / 80 = 1.5". Hence, the right magnification using this objective should be 60 / 1.5 = 40X. In practice, you can double this value, but it is better avoiding to go further, because the amount of visible detail will not increase. In the end, follow this simple rule: the magnification power of a telescope has not to exceed the diameter of its objective, expressed in mm. Check the real RP

of your instrument by means of double stars whose angular distances are tabulated in astronomical books.

例如，一个 80mm 直径的消色差物镜的分辨能力是 120/80 = 1.5。因此，使用这个物镜的正确放大倍率应该是 60/1.5 = 40X。在实际使用中，你可以将这个值乘以 2，但是最好不要距离这个值太远，因为你能看到的细节并不会增加。总而言之，有一个简单的规则：一个望远镜的最高放大倍率不会超过它的物镜直径的毫米数。通过观测天文学书籍里列出了角距的双星能够检测你的望远镜的真实分辨能力。

OBSERVATIONS AT THE TELESCOPE

通过望远镜观察

The most spectacular heavenly body to observe with a telescope is without a doubt the Moon. The best time to observe the Moon with your telescope is at the first quarter, when it appears only half illuminated. Under these conditions, lunar mountains and craters project long shadows, making them better visible from the Earth.

毫无疑问，通过望远镜看到的最壮观的天体是月球。观测月球的最佳时间是上弦月时，这个时候月球看起来只有一半被照亮。在这个条件下，月球表面的山脉和陨石坑投出很长的阴影，使得它们容易从地球上看到。

Make your first observations with the simple telescope, the one with the eyeglass lens as objective. At the beginning, keep the objective at the maximum aperture. At the edge of the objects, you can see the blue color at one side, and the orange color at the other side. These colors are produced by chromatic aberration. The image will appear quite confusing. Now place the diaphragm on the objective. It will greatly reduce the aberrations, you see the difference! But on the other hand, the brightness of the image will be dramatically decreased as will the resolving power. Using an achromatic telescope, instead, these defects are by comparison nearly imperceptible even without a diaphragm. In fact, with this type of instrument, the diaphragm is not needed.

使用物镜是老花镜片的第一台望远镜进行你的第一次观测。首先，让物镜有最大的通光口径，在观测物体的边缘，你能在一边看到蓝色，在另一边看到橙色。这些颜色就是由色差产生的。图像看起来会很模糊。现在你将光阑放到物镜前，它能大幅度减少色差，你看到的不同了！但是另一方面，图像的亮度和分辨率也大幅下降了。而如果使用一个消色差的望远镜，即使不使用光阑，这些效应也不明显。事实上，使用消色差望远镜观测，是不需要光阑的。

Other objects to observe are the nearest planets. Jupiter shows four satellites aligned along the equatorial plane, appearing as a model of the solar system. For observing the Rings of Saturn, you will need of an instrument of good quality and high magnification power. The comparison between the apparent sizes of Jupiter and Saturn give you an idea of great distances in astronomy. You can also see Venus, which shows phases as the Moon, and you can even see star clusters and double stars.

其它好的观测目标是离我们最近的一些大行星。观测木星能够看到它的赤道平面上的四个伽利略卫星，看其来就像一个小型的太阳系。为了能够观测土星的光环，你需要一个高质量和放大能力强的望远镜。对木星和土星看起来的大小的对比能让你对天文学中巨大的距离有一个直观的概念。你还可以观测金星，它表现出和月球一样的相位变化，你甚至还可以观测星团和双星。

WARNING:
DO NOT USE THE TELESCOPE TO OBSERVE THE SUN!
You will burn the retina of your eye!

警告：
禁止使用望远镜观察太阳！
否则你的眼睛的视网膜会被烧毁！

What you can do, instead, is to project the image of the Sun on a screen or on a wall of your room. You can do this during a solar eclipse. You will enjoy an amazing spectacle, which you can share with many friends.

你能够做的是，将太阳的像投影到一个屏上或者是房间的墙壁上。你还能够在日食时使用这种方法观测。你能领略到令人惊异的场景，并能与朋友们分享。

Terrestrial observations are also amusing. With the telescope, you can appreciate that the birds flying in your garden are not all sparrows, but also titmice, robins, finches, blackcaps, etc. With your telescope, you will be able to recognize the various species by their colored plumage. You can also observe the insects flying on the flowers, without getting your nose stung!

地面观察同样有趣。使用这个望远镜，你能发现在你的院子里飞过的鸟并不是都是麻雀，还有 titmice，robins，金丝雀，山雀等等。通过你的望远镜，你能够通过它们五彩的羽毛来认出它们。你还能够观看花朵上飞动的昆虫，而不用担心鼻子被蜇到。