Chapter 6 Solutions

6.1 (6.7) $M_T = (-s_{i1}/s_{o1})(-s_{i2}/s_{02}) = -s_i/s_o$. Let $s_o = \infty$ so that $s_o = s_{o1}$, $s_{i1} = f_1$, $s_{o2} = -(s_{i1} - d)$, $s_i = f$. Substituting into (6.7),

$$(-f_1/s_o)(-s_{i2}/-(s_{i1}-d)) = -f/s_o.$$

$$f = f_1(s_{i2}/(-s_{o2})) = f_1(s_{i2}/(s_{i1}-d)).$$

From

$$1/s_{o2} + 1/s_{i2} = 1/f_2;\ 1/s_{i2} = 1/f_2 - 1/s_{o2},\ s_{i2} = s_{o2}f_2/(s_{o2} - f_2).$$

$$f = (-f_1/s_{o2})(s_{o2}f_2/(s_{o2} - f_2))$$

$$= -f_1 f_2/(s_{o2} - f_2) = f_1 f_2/(s_{i1} - d + f_2).$$

$$1/f = (s_{i1} - d + f_2)/f_1 f_2 = 1/f_1 + (s_{i1} - d)/f_1 f_2.$$

But $s_{i1} = f_1$, so, $1/f = 1/f_1 + 1/f_2 - d/f_1 f_2$.

6.2 From Eq. (6.8), $1/f = 1/f' + 1/f' - d/f'f' = 2/f' - 2/3f'$, $f' = 3f'/4$.
From Eq. (6.9), $\overline{H_{11}H_1} = (3f'/4)(2f'/3)/f' = f'/2$. From Eq. (6.10), $\overline{H_{22}H_2} = -(3f'/4)(2f'/3)/f' = -f'/2$.

6.3 From Eq. (6.2), $1/f = 0$ when $-(1/R_1 - 1/R_2) = (n_l - 1)d/n_l R_1 R_2$. Thus $d = n_l(R_1 - R_2)/(n_l - 1)$.

6.4 $$\frac{1}{f} = (n_2 - 1)\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{(n_2-1)d}{n_2 R_1 R_2}\right)$$

Taking $d = 1$ cm, $R_1 = 10$ cm and $R_2 = -9$ cm,

$$\frac{1}{f} = 0.5\left[\frac{1}{10\text{ cm}} - \frac{1}{9\text{ cm}} + \frac{0.5(1\,cm)}{1.5(10\text{ cm})(9\text{ cm})}\right]$$

$$\frac{1}{f} = 0.0037\text{ cm}^{-1}$$

$$f = -270\text{ cm}$$

6.5 $1/f = 0.5[1/6 - 1/10 + 0.5(3)/1.5(6)10]$, $f = +24$;
$h_1 = -24(0.5)(3)/10(1.5) = -2.4$, $h_2 = -24(0.5)(3)/6(1.5) = -4$.

6.6 Since $|h_1| = |h_2|$ it follows from Eqs. (6.3) and (6.4) that $-f(n_l - 1)d_l/|R_2|n_l = -f(n_l - 1)d_l/|R_1|n_l$ and $|R_2| = |R_1|$ which means the lens is a sphere.

6.7 $f = (1/2)nR/(n-1)$; $h_1 = +R$, $h_2 = -R$.

6.8 This is a thick lens with $-R_2 = R_1 = R = 10$ cm and $d = 2R = 20$ cm.

(6.2) $$1/f = (n_l - 1)[1/R_1 - 1/R_2 + (n_l - 1)d/n_l R_1 R_2]$$
$$= (1.33 - 1)[1/10 - 1/(-10) + (1.33-1)(20)/1.33(10)(-10)];$$
$$f = 20.2\text{ cm}.$$

6.9 From Problem (6.6) or (6.7), (6.2) becomes $1/f = ((n_l - 1)/n_l)(2/R)$, with $R = +10$ cm. $1/f = ((1.4-1)/1.4)(2/10) = 0.057\text{cm}^{-1}$, $f = 17.5$ cm. (6.1) $1/f = 1/s_o + 1/s_i$, where s_o and s_i are measured from the principal planes. $1/s_i = 1/f - 1/s_o = 1/(17.5)\text{ cm} - 1/(400-10)\text{ cm}$; $s_i = 18.3$ cm. (6.7) $M_T = -s_i/s_o = -18.3/390 = -.047$. Image is real, inverted, and 0.047 times the size of the object.

6.10 (6.2) $1/f = (n_l - 1)[1/R_1 - 1/R_2 + (n_l - 1)d/n_l R_1 R_2]$;

$$(1.5 - 1)[1/23 - 1/20 + (1.5 - 1)(9.0)/1.5(23)(20)] = 0,$$

$f = \infty$.

Generally, if

$$1/f = 0,\ [1/R_1 - 1/R_2 + (n_l - 1)d/n_l R_1 R_2] = 0;$$

$$\frac{n_l R_2}{n_l R_1 R_2} - \frac{n_l R_1}{n_l R_1 R_2} + \frac{(n_l - 1)\, d}{n_l R_1 R_2} = 0$$

$$(n_l - 1)d = n_l(R_1 - R_2);\quad (R_1 - R_2) = (n_l - 1)n_l d$$

for $n_l = 1.5$, $(R_1 - R_2) = ((1.5-1)/1.5)d = d/3$.

6.11 $f = 29.6 + 4.0 = 33.6$ cm; $s_o = 49.8 + 2 = 51.8$ cm; $\dfrac{1}{51.8} + \dfrac{1}{s_i} = \dfrac{1}{33.6}$

$s_i = 95.6$ cm from H_2 and 91.6 cm from the back face.

6.13 From Eq. (6.2),

$$1/f = (1/2)[1/4.0 - 1/(-15) + (1/2)4.0/(3/2)(4.0)(-15)] = 0.147$$

and $f = 6.8$ cm. $h_1 = -(6.8)(1/2)(4.0)/(-15)(3/2) = +0.60$ cm, while $h_2 = -2.3$. To find the image $1/(100.6) + 1/s_i = 1/(6.8)$; $s_i = 7.3$ cm or 5 cm from the back face of the lens.

6.14 For both, $-R_2 = R = R_1$, so (6.2) becomes:

$$\frac{1}{f} = (n-1)\left[\frac{2}{R} - (n-1)\frac{d}{nR^2}\right]$$

$$\frac{1}{f} = (1.5-1)\left[\frac{2}{50} - (1.5-1)\frac{5.0}{1.5(50)^2}\right];\ f = 50.8\text{ cm}$$

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} = 26.7\text{ cm}$$

6.15 (6.8) $1/f = 1/f_1 + 1/f_2 - d/f_1 f_2 = 1/(+20) + 1/(-20) - 10/(20)(-20)$; $f = +40$ cm. The principal planes are found from (6.9) and (6.10).

(6.9) $\overline{H_{11}H_1} = fd/f_2 = (+40)(10)/(-20) = -20$ cm.

(6.10) $\overline{H_{22}H_2} = fd/f_1 = (+40)(10)/(20) = +20$ cm.

6.16 $R_1 = \begin{bmatrix} 1 & -D_1 \\ 0 & 1 \end{bmatrix}$ from (6.16) where

$D_1 = (n-1)/R_1 = (1.5-1)/2.5\text{ cm} = 0.2\text{ cm}^{-1}$.

$$T_{21} = \begin{bmatrix} 1 & 0 \\ d_{21}/n & 1 \end{bmatrix} \quad (6.24)$$

$$= \begin{bmatrix} 1 & 0 \\ 1.2/1.5 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0.8 & 1 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 1 & -D_2 \\ 0 & 1 \end{bmatrix}$$

but $R_2 = \infty$, so $D_2 = 0$.

(6.29) $A = R_2 T_{21} R_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 0.8 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0.2 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0.2 \\ 0.8 & 1.16 \end{bmatrix}$

Check: $|A| = 1(1.16) - 0.2(0.8) = 1$.

6.17 $$R_1 = \begin{bmatrix} 1 & -\left(\dfrac{n_{t1} - n_{i1}}{R_1}\right) \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -\left(\dfrac{1.81 - 1.00}{11.0}\right) \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -0.0736 \\ 0 & 1 \end{bmatrix}$$

$$T_{21} = \begin{bmatrix} 1 & 0 \\ \frac{d}{n} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \dfrac{3.00}{1.81} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1.657 & 1 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 1 & -\left(\dfrac{n_{t2} - n_{i2}}{R_2}\right) \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -\left(\dfrac{1.00 - 1.81}{-120}\right) \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -6.75\times10^{-3} \\ 0 & 1 \end{bmatrix}$$

$$A = R_2 T_{21} R_1 = \begin{bmatrix} 1 & -6.75\times10^{-3} \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 1.657 & 1 \end{bmatrix}\begin{bmatrix} 1 & -0.0736 \\ 0 & 1 \end{bmatrix}$$

$$A = \begin{bmatrix} 0.989 & -6.75\times10^{-3} \\ 1.657 & 1 \end{bmatrix}\begin{bmatrix} 1 & -0.0736 \\ 1.657 & 1 \end{bmatrix}$$

$$A = \begin{bmatrix} 0.989 & -0.080 \\ 1.657 & 0.876 \end{bmatrix}$$

6.18 When the object and image are both in air, $n_I = n_o = 1$. Since the distance between the vertex and the object is negative, take d_0 is taken to be a negative.

$$\begin{bmatrix} \alpha_I \\ y_I \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ d_I & 1 \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -d_o & 1 \end{bmatrix}\begin{bmatrix} \alpha_0 \\ y_0 \end{bmatrix}$$

$$\begin{bmatrix} \alpha_I \\ y_I \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{11}d_I + a_{21} & a_{12}d_I + a_{22} \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -d_o & 1 \end{bmatrix}\begin{bmatrix} \alpha_0 \\ y_0 \end{bmatrix}$$

$$\begin{bmatrix} \alpha_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} a_{11} - d_o a_{12} & a_{12} \\ d_1(a_{11} - a_{12}d_o) + a_{21} - d_o a_{22} & a_{12}d_1 + a_{22} \end{bmatrix}\begin{bmatrix} \alpha_0 \\ y_0 \end{bmatrix}$$

$$\begin{bmatrix} \alpha_I \\ y_I \end{bmatrix} = \begin{bmatrix} \alpha_0(a_{11} - d_o a_{12}) + a_{12}y_0 \\ \alpha_0[d_I(a_{11} - a_{12}d_o) + a_{21} - d_o a_{22}] + y_0(a_{12}d_I + a_{22}) \end{bmatrix}$$

$$y_1 = \alpha_0[d_I(a_{11} - a_{12}d_o) + a_{21} - d_o a_{22}] + y_0(a_{12}d_I + a_{22})$$

6.19 Equation (6.36) is:

$$d_{I2} = \frac{-a_{21} + a_{22}d_{10}}{a_{11} - a_{21}d_{10}}$$

Where the matrix A is given by equation (6.31):

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} 1-\dfrac{D_2 d_l}{n_l} & -D_1 - D_2 + \dfrac{D_1 D_2 d_l}{n_l} \\ \dfrac{d_l}{n_l} & 1-\dfrac{D_1 d_l}{n_l} \end{bmatrix}$$

In the case of a thin lens, $d_l \to 0$

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} 1 & -D_1 - D_2 \\ 0 & 1 \end{bmatrix}$$

Then (6.36) becomes:

$$d_{I2} = \frac{0 + d_{1o}}{1 + (D_1 + D_2) d_{1o}}$$

Using $D_1 = \dfrac{n_l - 1}{R_1}$ and $D_2 = \dfrac{n_l - 1}{R_2}$, then

$$(D_1 + D_2) = \frac{1}{f}$$

And,

$$d_{I2} = \frac{d_{1o}}{1 + \dfrac{d_{1o}}{f}}$$

$$\frac{1}{S_o} + \frac{1}{S_I} = \frac{1}{f}$$

$$1 + \frac{S_o}{S_I} = \frac{S_o}{f}$$

$$\frac{S_o}{S_I} = \frac{S_o}{f} - 1$$

$$S_I = \frac{S_o}{\dfrac{S_o}{f} - 1} = \frac{-S_o}{1 - \dfrac{S_o}{f}}$$

This is equivalent to $d_{I2} = \dfrac{d_{1o}}{1 + \frac{d_{1o}}{f}}$, when one keeps in mind the fact that when $S_o > 0$, $d_{1o} < 0$.

6.20 Working in centimeters,

$$D_1 = (2.4 - 1.9)/R_1 = 0.1\text{ cm}^{-1},\ D_2 = (1.9 - 2.4)/R_2 = -0.05\text{ cm}^{-1}$$

therefore

$$A = \begin{bmatrix} 1 & -D_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ d/n_l & 1 \end{bmatrix} \begin{bmatrix} 1 & -D_1 \\ 0 & 1 \end{bmatrix}$$

$$A = \begin{bmatrix} 1 & 0.05 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0.4 & 1 \end{bmatrix} \begin{bmatrix} 1 & -0.1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1.02 & -0.052 \\ 0.4 & 0.96 \end{bmatrix}$$

(1.02) (0.96) – (0.4) (– 0.052) = 0.979 + 0.0208 = 1.

6.21 We have

$$\det A = a_{11}a_{22} - a_{12}a_{21} = 1 - (D_1 + D_2)d_{21}/n_{t1} + D_1 D_2 d_{21}^2/n_{t1}^2$$
$$+(D_1 + D_2)d_{21}/n_{tl} + D_1 D_2 d_{21}^2/n_{t1}^2 = 1.$$

6.22 $h_1 = n_{i1}(1 - a_{11})/(-a_{12}) = (D_2 d_{21}/n_{t1})f = -(n_{t1} - 1)d_{21} f/R_2 n_{t1}$, from Eq. (5.70) where $n_{t1} = n_l$; $h_2 = n_{t2}(a_{22} - 1)/(-a_{12}) = -(D_1 d_{21}/n_{t1})f$ from Eq. (5.71), $h_2 = -(n_{i1} - 1)d_{21} f/R_1 n_{t1}$.

6.23 $A = R_2 F_{21} R_1$, but for the planar surface

$R_2 = \begin{bmatrix} 1 & D_2 \\ 0 & 1 \end{bmatrix}$ and $D_2 = (n_{t1} - 1)/(-R_2)$ but $R_2 = \infty$ $R_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

which is the unit matrix, hence $A = F_{21} R_1$.

6.24 $D_1 = (1.5 - 1)/0.5 = 1$ and $D_2 = (1.5 - 1)/-(-0.25) = 2$, $A = \begin{bmatrix} 0.6 & -2.6 \\ 0.2 & 0.8 \end{bmatrix}$

and $|A| = 0.48 + 0.52 = 1$.

6.25 From the equation above (6.39),

$$-0.2 = -a_{12} = (n_{t1} - 1)\left\{\frac{1}{R_1} + \frac{1}{R_2}\left[\frac{(n_{t1} - d_{21})}{R_1 n_{t1}} - 1\right]\right\}.$$

Solving for the reciprocal of the second radius gives

$$\frac{1}{R_2} = -\left[a_{12} + \frac{(n_{t1} - 1)}{R_1}\right]\frac{R_1 n_{t1}}{(n_{t1} - 1)}\frac{1}{(n_{t1} - d_{21} - R_1 n_{t1})} = 4\text{ cm}^{-1}.$$

Then $R_2 = 0.25$ cm.

6.26 Starting with the three 2×2 matrices from Eq. (6.33):

$$\begin{bmatrix} 1 & 0 \\ d_I & 1 \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -d_o & 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{11}d_I + a_{21} & a_{12}d_I + a_{22} \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -d_o & 1 \end{bmatrix}$$
$$= \begin{bmatrix} a_{11} - d_o a_{12} & a_{12} \\ d_I(a_{11} - a_{12}d_o) + a_{21} - d_o a_{22} & a_{12}d_I + a_{22} \end{bmatrix}$$

Then use Eq. (6.35): $d_I(a_{11} - a_{12}d_o) + a_{21} - d_o a_{22} = 0$, and Eq. (6.37) $M_T = a_{12}d_I + a_{22}$:

$$= \begin{bmatrix} a_{11} - d_o a_{12} & a_{12} \\ 0 & M_T \end{bmatrix}$$

Now take:

$$\det\begin{bmatrix} a_{11} - d_o a_{12} & a_{12} \\ 0 & M_T \end{bmatrix} = (a_{11} - d_o a_{12})M_T = 1$$
$$M_T = \frac{1}{(a_{11} - d_o a_{12})}$$

6.27 $R_1 = \begin{bmatrix} 1 & -D_1 \\ 0 & 1 \end{bmatrix}$ from (6.16) where

$$D_1 = (n-1)/R_1 = (3/2-1)/-10.0 \text{ cm} = -0.050 \text{ cm}^{-1}.$$

$$T_{21} = \begin{bmatrix} 1 & 0 \\ d_{21}/n & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1.00/1.50 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0.67 & 1 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 1 & -D_2 \\ 0 & 1 \end{bmatrix}$$

But $R_2 = \infty$, so $D_2 = 0$.

(6.29) $A = R_2 T_{21} R_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0.67 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0.05 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0.05 \\ 0.67 & 1.03 \end{bmatrix}$

Check: $|A| = 1(1.03) - (0.05)(0.67) = 1.$

$$\begin{bmatrix} n_t\alpha_t \\ y_t \end{bmatrix} = A \begin{bmatrix} n_i\alpha_i \\ y_i \end{bmatrix}$$

$$\alpha_t = 0,\ n_i = 1,\ y_t = y_i.$$

$$\begin{bmatrix} 0 \\ y_i \end{bmatrix} = A \begin{bmatrix} \alpha_i \\ y_i \end{bmatrix} = \begin{bmatrix} 1 & 0.05 \\ 0.67 & 1.03 \end{bmatrix} \begin{bmatrix} \alpha_i \\ y_1 \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ y_i \end{bmatrix} = \begin{bmatrix} \alpha_i + (0.05)y_i \\ (0.67)\alpha_i + (1.03)y_i \end{bmatrix}$$

$$0 = \alpha_i + (0.05)y_i,\ \ y_i = (0.67)\alpha_i + (1.03)y_i,$$

both yield $\alpha_i = (-0.05)(2.0) = -0.10$ or 0.10 radians above the axis.

6.28 (6.34) $1/f = -a_{12} = -(D_1 + D_2 - D_1 D_2 d/n_l);$

$$D_1 = (n_l - 1)/R_1 = (1.5-1)/0.5 = 1.0;$$

$$D_2 = (n_l - 1)/R_2 = (1.5-1)/(-0.25) = -2.0.$$

$$1/f = -(1.0 - 2.0 - (1.0)(2.0)(0.3)/1.5), \quad f = 0.71.$$

$$\overline{V_1H_1} = (1)(1 - a_{11})/-a_{12},$$

(6.36) $a_{11} = 1 - D_2 d/n_l = 1 - (-2.0)(0.3)/1.5 = 1.4.$

$$\overline{V_1H1} = (1-1.4)/1.4 = -0.29.$$

(6.37) $\overline{V_2H_2} = (1)(a_{22} - 1)/-a_{12};$

$$a_{22} = 1 - (D_1 d)/n_l = 1 - (1.0)(0.3)/1.5 = 0.8;$$

$$\overline{V_2H_2} = (0.8-1)/1.4 = -0.14.$$

6.29 For two reflections

$$\begin{bmatrix} -1 & -2/(+r) \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -d & 1 \end{bmatrix}\begin{bmatrix} -1 & -2/(-r) \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ d & 1 \end{bmatrix}$$

and this yields the desired matrix. When $d = r$ the matrix for two traversals becomes

$$\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$$

and for four it is

$$\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

and since this is a unit matrix the light ray is back to where it started.

6.30 See E. Slayter, *Optical Methods in Biology.*

$$\overline{PC}/\overline{CA} = (n_1/n_2)R/R = n_1/n_2,$$

while $\overline{CA}/\overline{P'C} = n_1/n_2$. Therefore triangles ACP and ACP' are similar; using the sine law

$$\sin\angle P'AC/\overline{PC} = \sin\angle APC/\overline{CA}$$

or $n_2 \sin\angle P'AC = n_1 \sin\angle APC$, but $\theta_i = \angle P'AC$, thus

$$\theta_t = \angle APC = \angle P'AC,$$

and the refracted ray appears to come from P'.

6.31 From Eq. (5.6), let $\cos\varphi = 1-\varphi^2/2$; then

$$l_o = [R^2 + (s_o + R)^2 - 2R(s_o + R) + R(s_o + R)\varphi^2]^{1/2},$$
$$l_o^{-1} = [s_0^2 + R(s_o + R)\varphi^2]^{-1/2}, \quad l_i^{-1} = [s_i^2 - R(s_i - R)\varphi^2]^{-1/2},$$

where the first two terms of the binomial series are used,

$$l_0^{-1} \approx s_0^{-1} - (s_o + R)h^2/2s_o^3R$$

where

$$\varphi \approx h/R, \quad l_i^{-1} \approx s_i^{-1} + (s_i - R)h^2/2s_i^3R.$$

Substituting into Eq. (5.5) leads to Eq. (6.40).

6.33 Because (a) is symmetrical and looks like a somewhat altered Airy pattern; this is spherical aberration. (b) This pattern is asymmetrical as if the Airy system were pulled off to the side, so it corresponds to a little coma. (c) This pattern is asymmetrical along two axes and must be due to astigmatism.

6.34 Fig. P.6.34a is bi-axially asymmetric and therefore corresponds to astigmatism. (b) is elongated along one axis and is due to coma, and because the pattern isn't very complicated there isn't much of it.