PERFORMANCE OF COMMERCIAL CCD CAMERAS WHEN COUPLED TO SMALL TELESCOPES (3 - 12 INCH)

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Presented at the 3rd AAVSO CCD Workshop, June 6, 1993

Abstract

CCDs have had a revolutionary effect on large, mountain-top astronomy (40- to 160-inch telescopes), and, more recently, on smaller, urban and suburban university astronomy research (12- to 200-inch telescopes). This paper explores the theoretical capabilities of a range of CCD cameras and sites and compares them to actual results using 3- to 12-inch telescopes. The detection of stars to 16th and 21st magnitudes with these instruments with signal-to-noise ratios of 3 to 10 is documented. The conclusion is that amateur astronomers with 3-inch telescopes and CCD cameras from suburban sites can make valuable contributions to AAVSO programs.

1. Introduction

During the last few years the CCD revolution has been underway in the amateur community. Many of the initial users of this technology are former astrophotographers, as am I, and probably approach this new technology with strong bias from their prior experiences.

I was unaware of the CCD revolution in 1989 and, based on five years of astrophotography, developed a set of biases, principles, and priorities. These were, in order of importance: big aperture, dark site, permanent observatory, digital setting circles, autoguider, and camera and film.

As a result of these factors the Bailey Hill Observatory was established near the White Mountains of New Hampshire, far from the light pollution of the suburbs of Boston where astrophotography was not possible. In the summer of 1989, in the midst of construction, I attended an astronomy conference where five manufacturers were demonstrating their latest CCD equipment. In a discussion with one of the manufacturers, a comment was made that "when CCDs perform as well as film, I would be interested." The manufacturer replied that CCDs were already better than film. Later in the conference, from the roof of the parking garage of the Boston Museum of Science, with sufficient light pollution that the location of Polaris was difficult, the manufacturer took a 30-second exposure of M-57 which showed the central star clearly. That experience resulted in my conversion to CCD imaging exclusively and has caused me to shuffle the above mentioned priorities nearly inversely! In order to understand this, the theoretical capabilities of CCD systems are discussed and compared to actual experience.

2. Theory

The detection of a desired object on film is often described in terms of its contrast on the resulting negative or print. The analogous description for a CCD image is the signal-to-noise ratio (S/N) which also describes the success of an image. Many excellent derivations of the S/N ratio of an operating CCD camera system have appeared in the literature (Howell 1992) and need not be repeated. In addition, an excellent article on mechanizing these equations was written by Sinnott and Mallama (1993). These two works were expressed in a spreadsheet that would allow exploration of the impact of such factors as aperture, sky background, dark current, readout noise, pixel size, and exposure. The spreadsheet calculated the resulting S/N ration for any combination of the above factors. This also allowed the presentation of a large quantity of data in graphical form for easy communication. These graphs form the basis for the following discussion.

3. Signal-to-Noise Ratio Equates to Speed

A typical spreadsheet output is shown in Table 1 for various commercial CCD cameras with the specifications derived from manufacturer's data sheets. These CCD cameras range from $1,000 to $30,000 and represent what is currently available in the commercial market. These also cover the range from an SBIG 165 x 192 pixel chip with air cooling operating at 8 bits to a Photometrics 512 x 512 pixel chip with liquid and thermoelectric cooling operating at 16 bits in the MPP mode. The input parameters are listed in the first column while the resulting S/N for various exposures is summarized in the bottom row.

The results of Table 1 are shown in graphical form in Figure 1, which shows the exposure time required to achieve a S/N of 11 for a 20th magnitude star with a 24th magnitude per square arc-second sky, using a 12-inch telescope. The range of exposures from 2600 seconds to a speedy 55 seconds is what the performance/cost differences of CCD systems provide. While the differences are substantial, we should not overlook the potential of the detection of 20th magnitude objects for future AAVSO or university projects.

Table 1. Comparison of Commercial CCD Cameras Showing Magnitude, Exposure, and Signal-to-Noise.

COMPARISON OF VARIOUS COMMERCIAL CCD CAMERAS--PERFECT SKY = 24 th MAGNITUDE						
					REF: Sky & Tel, Feb 93	
	SBIG-ST4	SBIG-ST6	PM * 1A	PM * 1	PM S200	MPP
AP-aperature (in)	12.00	12.00	12.00	12.00	12.00	12.00
SB-sky brtness (m/sec^2)	24.00	24.00	24.00	24.00	24.00	24.00
PS-pix size (arc-secs)	3.64	3.64	3.64	3.64	3.64	3.64
DD-detector dia (arc-sec)	3.00	3.00	3.00	3.00	3.00	3.00
RN-read noise (e/pix)	300.00	40.00	15.00	15.00	6.00	5.88
TH-thermal noise (e/pix/s)	300.00	70.00	48.00	8.00	3.00	0.14
ET-time long exp (secs)	100.00	100.00	100.00	100.00	100.00	100.00
SO-star sig const (e/sec)	2000000	2000000	2000000	2000000	2000000	2000000
PI	3.14	3.14	3.14	3.14	3.14	3.14
AR-det area (arc-sec^2)	7.07	7.07	7.07	7.07	7.07	7.07
PX-det area (pixels)	0.53	0.53	0.53	0.53	0.53	0.53

S-exposure time (secs)	2600.00	610	425	125	76	55
M-object magnitude	20.00	20.00	20.00	20.00	20.00	20.00
L-luminosity	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-08
SG-total signal	7.49E+03	1.76E+03	1.22E+03	3.60E+02	2.19E+02	1.58E+02
SK-sky total	1.33E+03	3.12E+02	2.17E+02	6.39E+01	3.89E+01	2.81E+01
TT-thermal total	4.16E+05	2.28E+04	1.09E+04	5.33E+02	1.22E+02	4.11E+00
N-number of frames	1	1	1	1	1	1
S/N-signal to noise	10.89	10.96	10.97	10.97	10.96	10.95

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4. The Effect of Aperture

The systems summarized in Figure 1 represent the performance of a 12-inch telescope. The same spreadsheet may be used to evaluate the impact of aperture on the detection of faint stars. Figure 2 summarizes the magnitude which may be imaged by telescopes of 3- to 12-inch aperture using 17th magnitude per square arc-second sky background and the Photometrics S-200 CCD camera. Even exposures of 10 seconds are capable of reaching magnitudes 16.5 and 18 with a S/N = 3, using 3 to 12 inches of aperture, respectively. This is certainly beyond the capabilities of the typical backyard observatory of only a few years ago. It also serves to illustrate the complexity and cost of a 12-inch telescope versus a 3-inch telescope. The 3-inch telescope only lowers the limit of detection by about 1.5 magnitudes.

The detection of objects and the photometry of them should be kept in perspective. The S/N = 3 represents a lower limit of detection of an object from the background. Photometry would have errors of perhaps 0.3 to 0.5 magnitude (to first order, the accuracy is inversely proportional to the S/N ratio). For some projects, this might be an improvement over existing capabilities, for example, a variable whose minima are fainter than 13th magnitude or so, the limit for many observers not using a CCD. On the other hand, projects requiring 0.005 magnitude accuracy would require a minimum S/N of 200. In addition, precision of 0.005 magnitude introduces many issues besides S/N. While resolution to two decimal places is easy, accuracies to and repeatability of significantly better than 0.1 magnitude require very careful techniques. However, for the purpose of imaging a faint star or galaxy, the S/N = 3 is a reasonable lower limit.

5. Influence of Detector Noise

Let's explore the effect of detector noise. Here we are using detector noise to include all the dark current and read noise of the CCD camera system. As an oversimplified approach, Figure 3 shows the limiting magnitude attainable by three commercial CCD cameras which bracket the performance available at this time. What is surprising is that the moderately priced SBIG ST4 attains 18.5 magnitude under 24th magnitude-per-arc-second skies with a 12-inch telescope in 100 seconds. At the other end of the spectrum, a 22nd magnitude object can be imaged with the same exposure using a high performance Photometrics S-200. Once again the law of diminishing returns is clearly evident.

6. Effect of Aperture, Detector, and Sky Combined

Figures 4 and 5 show the effects of combining aperture, detector noise, and sky conditions. Figure 4 shows that when we combine a simple 3-inch telescope with a high performance CCD camera we obtain nearly the same results as when we combine a simple CCD camera and a 12-inch telescope. Once again 17- to 18-magnitude objects are just detectable with a sky of 17th magnitude per square arc-second, a S/N = 3, and an exposure of 100 seconds. Figure 5 shows that the range expands from magnitude 15.5 to 21.5 when the moderate combination of 17th magnitude per arc-second sky, 3-inch telescope, and SBIG ST4 CCD camera is compared to the combination of 22nd magnitude per arc-second sky, 12-inch telescope, and Photometrics S-200 CCD camera. This difference of 6 magnitudes in performance is roughly the sum of 2 magnitudes each from the effects of aperture, detector noise, and sky.

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7. Effect of Sky Background

Most astrophotographers have found that dark skies are essential for good film photography. One would expect that the same would be true for CCD imaging. This does not seem to be the case, as many who have tried CCD imaging from a suburban site have obtained remarkable results (DiCicco 1993). This phenomenon was also explored via a spreadsheet. The results are plotted in Figure 6. It shows that a 17.5-magnitude object can be imaged from a 15th magnitude-per-square-arc-second sky using a 12-inch telescope with a S/N = 3 in 100 seconds. A sky background of 15th magnitude per arc-second represents late twilight and is brighter than the backyard skies of most observers. A desert mountain top observatory typically has 22nd magnitude-per-square-arc-second skies, while the Hubble Space Telescope probably has 28th magnitude. The typical suburb has about 17th magnitude while the typical amateur dark site has probably 20th magnitude.

The potential user of CCD's should also understand that since the sky intensity is a noise process to the CCD, its buildup is proportional to the square root of the exposure time, so it is possible to image an object fainter than the background sky with the proper exposure.

8. Correlation with Actual Results

Prior to the preparation of any of the above analyses, I was performing some imaging from my suburban backyard and was shocked at the success. The performance that could be obtained under good conditions was starting to be published, but amateurs had not tried from poor to good sites. During some recreational imaging, a 16th magnitude star was detected in a 30-second exposure with a 3-inch refractor. This performance was corroborated by DiCicco (1992), who recorded a magnitude 15.7 star with a 10-second exposure during twilight from a similar site with an 11-inch telescope. This performance is consistent with that shown in Figure 2.

Figures 7 and 8 show two images of the lensed quasar in Ursa Major, QSO 0957 + 561 A and B. The object is reported at about magnitude 16.5 but is believed to be 5 billion light years from earth. To my knowledge, this is the farthest distance imaged by an amateur astronomer at this time with a CCD. Figure 7 is taken with a 6-inch f/3.3 Hyperbolic Astrograph from a dark site with a 300-second exposure. The QSO is clearly evident along with NGC 3079 and 3073, but because of the small image scale the 6 arc-second separation is not clearly shown. Figure 8 shows a portion of that same field imaged with a 12-inch f/3.8 Hyperbolic Astrograph with eyepiece projection giving an overall f/12.5. The separation along with a 17.8 magnitude star is clearly shown with a 300-second exposure. Figure 6 suggests that this performance is clearly possible.

This same figure also shows that an upper limit of 20th to 22nd magnitude should be possible in 600 seconds. This limit was assessed by imaging the field SA57 around star SAO 82672. The results are shown in Figure 9, along with the magnitude estimates taken from Wallis and Provin (1988), indicating detection of magnitude 21.0 in 600 seconds. This result agrees with the above theory very well. Careful image processing of this same field also shows that star SAO 82672 has a companion. Unfortunately, it is only visible on the computer monitor and attempts to make a hard copy have not been successful.

9. Conclusions

The following conclusions are evident:

1. The S/N calculations appear to be in good agreement with actual performance.
2. Telescopes as small as 3 inches are capable of imaging to 16th magnitude and should be quite useful for many AAVSO projects when equipped with a CCD camera.
3. These results are not significantly affected by the sky background, making backyard CCD photometry feasible, which should result in better participation.
4. Astrophotographers converting to CCD imaging may find that their priorities are revised in order of importance to: low noise detector, permanent observatory, digital setting circles, autoguider, dark site, big aperture.

References

DiCicco, D. 1992, "A Remarkable New CCD Camera," in *Sky & Telescope,* October, 395.

DiCicco, D. 1993, "The Universe in Color," in *Sky & Telescope,* May, 34-39.

Howell, S. B. 1992, "Introduction to Differential Time-Series Astronomical Photometry Using Charge Coupled Devices," in *Astron. Soc. Pacific Conference Series,* 23, 112-114.

Sinnott, R. W., and Mallama, A. 1993, "The Limiting Magnitude of a CCD Camera," in *Sky & Telescope,* February, 84-86.

Wallis, B. D. and Provin, R. W. 1988, *Advanced Astrophotography Techniques,* Cambridge University Press, Cambridge, 96.

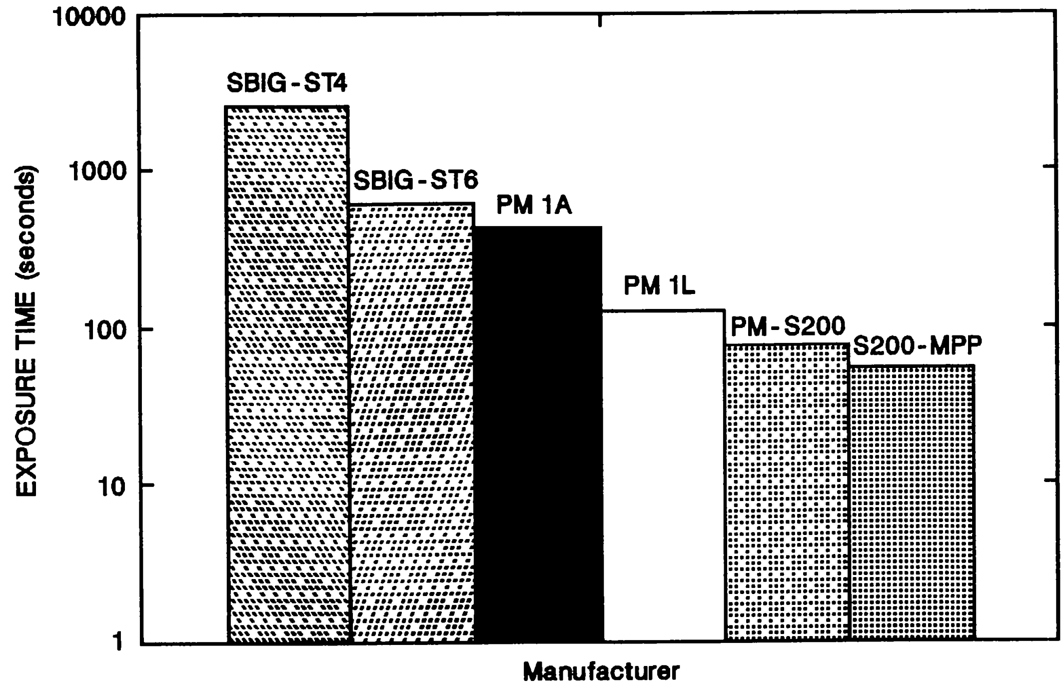

Figure 1. Exposure time required to achieve a signal-to-noise ratio of 11 for a 20th magnitude star with a 24th magnitude per square arc-second sky, using a 12-inch telescope and the CCD cameras described in Table 1.

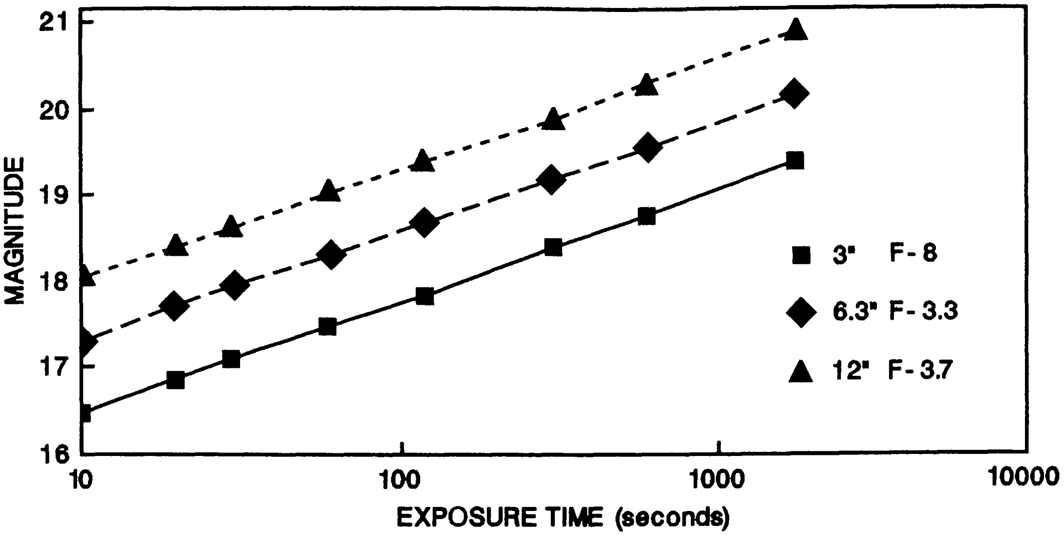

Figure 2. Summary of the magnitude which may be imaged by 3- to 12-inch telescopes using 17th magnitude per square arc-second sky background and the Photometrics S-2000 CCD camera.

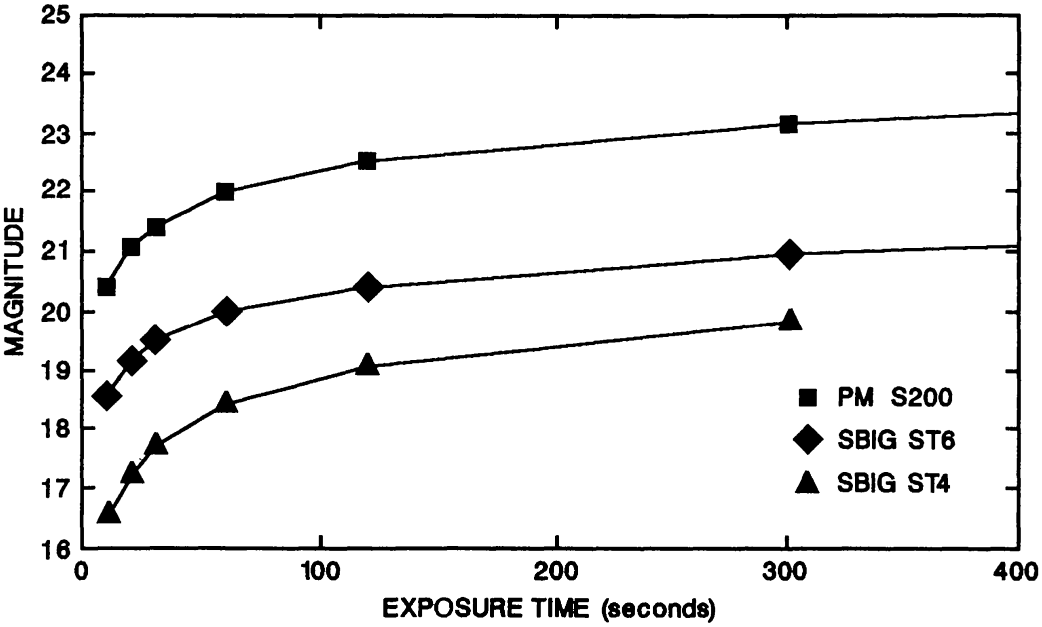

Figure 3. Limiting magnitude attainable by the three commercial CCD cameras indicated, used with a 12-inch telescope.

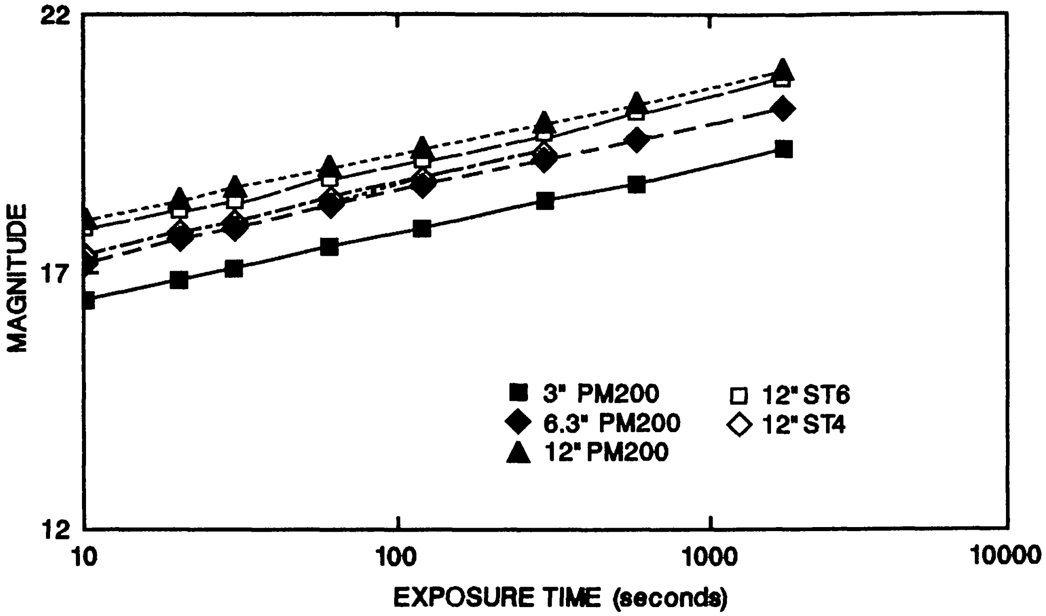

Figure 4. The effects of the combination of aperture and CCD camera type (detector noise) with 17th-magnitude-per-square-arc-second sky conditions. In our tests, a simple 3-inch telescope combined with a high-performance CCD camera yields nearly the same results as a 12-inch telescope with a simple CCD camera.

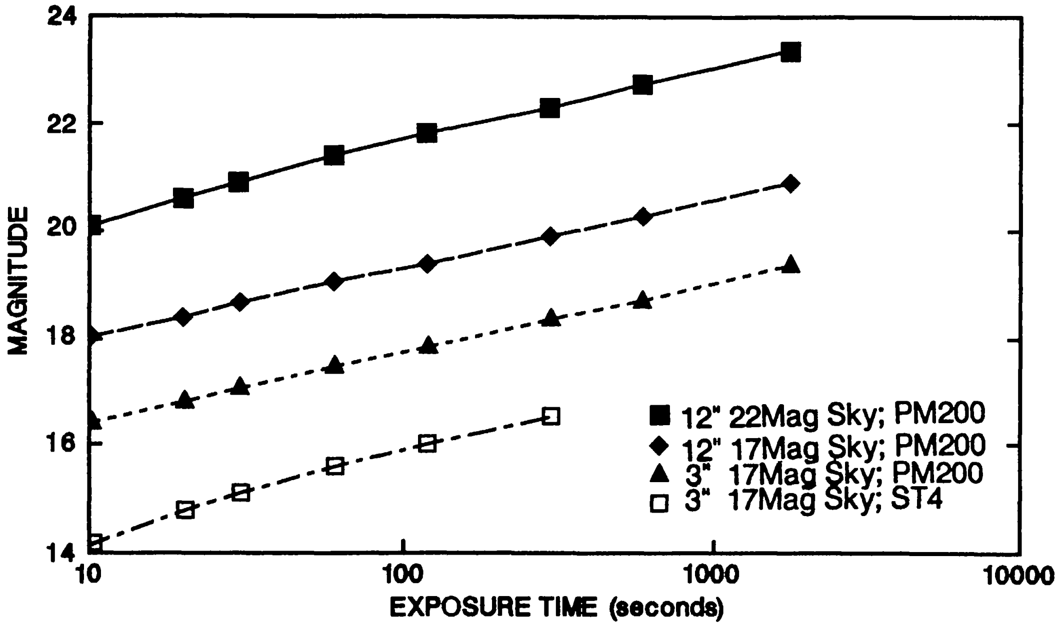

Figure 5. The moderate combination of 17th magnitude per arc-second sky, 3-inch telescope, and SBIG ST4 CCD camera is compared to the combination of 22nd- and 17th-magnitude-per-square-arc-second sky, 12- and 3-inch telescopes, and Photometrics S-200 CCD camera. This difference of 6 magnitudes in performance is roughly the sum of 2 magnitudes each from the effects of aperture, detector noise, and sky.

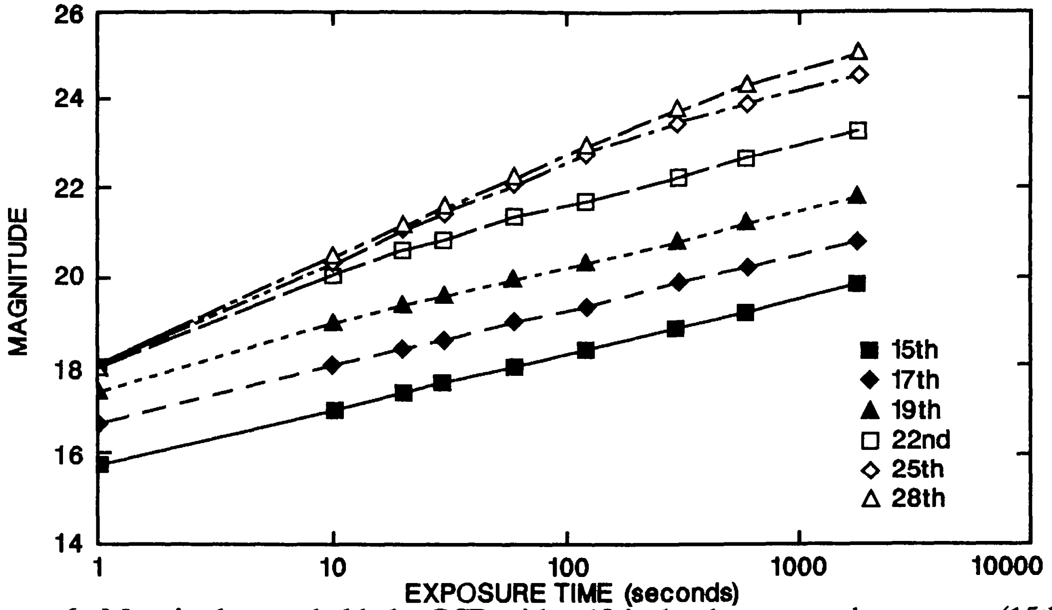

Figure 6. Magnitudes reachable by CCD with a 12-inch telescope under a range (15th - 28th) of magnitude-per-square-arc-second sky conditions.

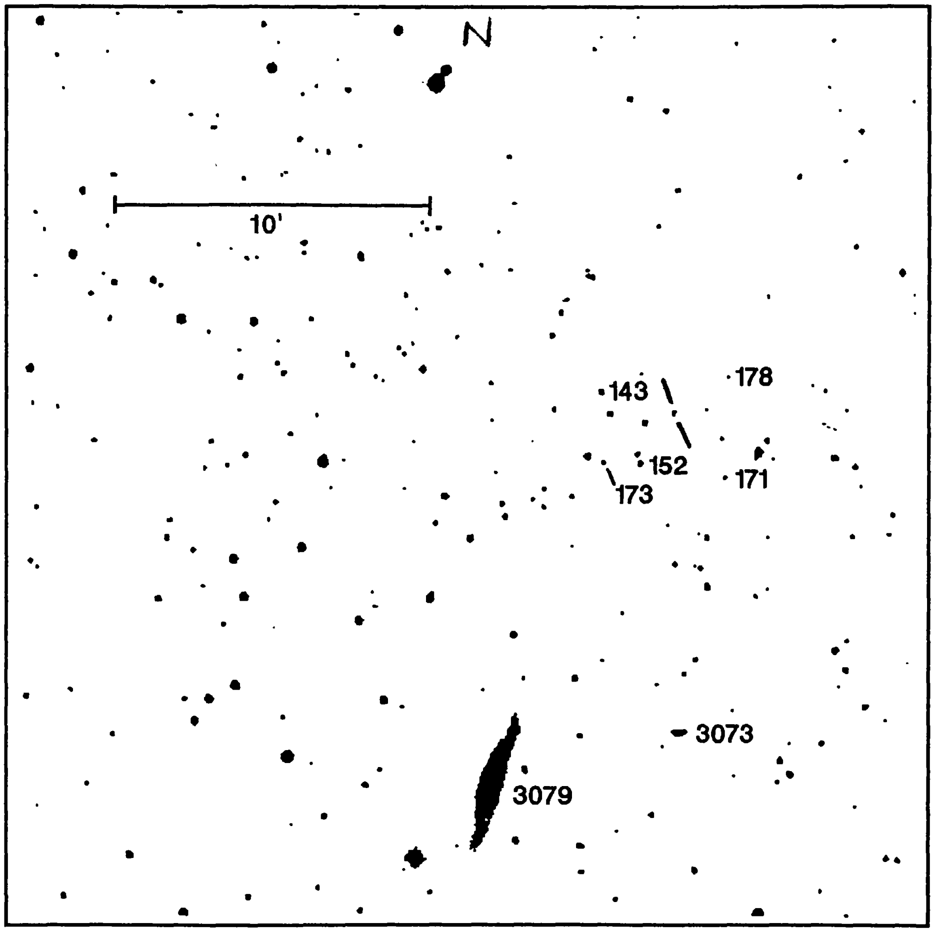

Figure 7. An exposure of the lensed quasar in Ursa Major, QSO 0957+561 A and B, taken with a 6-inch f/3.3 Hyperbolic Astrograph from a dark site with a 300-second exposure. This QSO, believed to be 5 billion light years away, is clearly evident along with NGC 3079 and 3073, but because of the small image scale the 6 arc-second separation between A and B is not clearly shown.

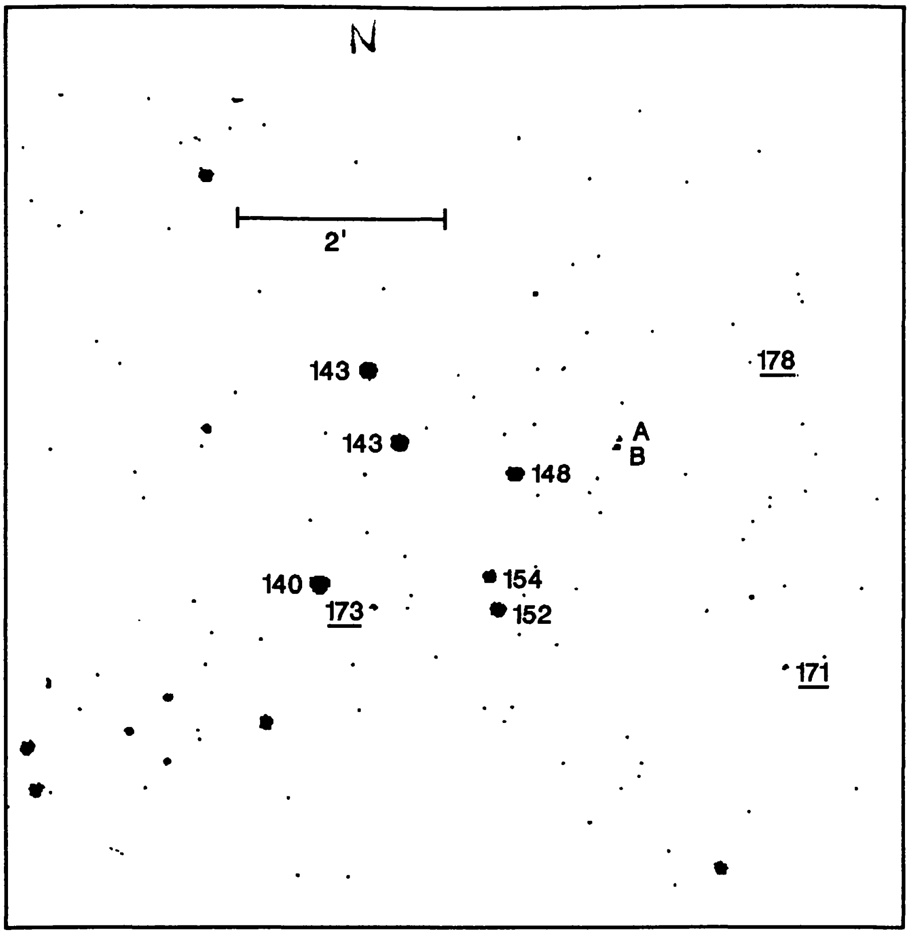

Figure 8. A portion of the field shown in Figure 7, imaged with a 12-inch f/3.8 Hyperbolic Astrograph with eyepiece projection, giving an overall f/12.5. The separation between A and B, along with a 17.8 magnitude star, is clearly shown with a 300-second exposure.

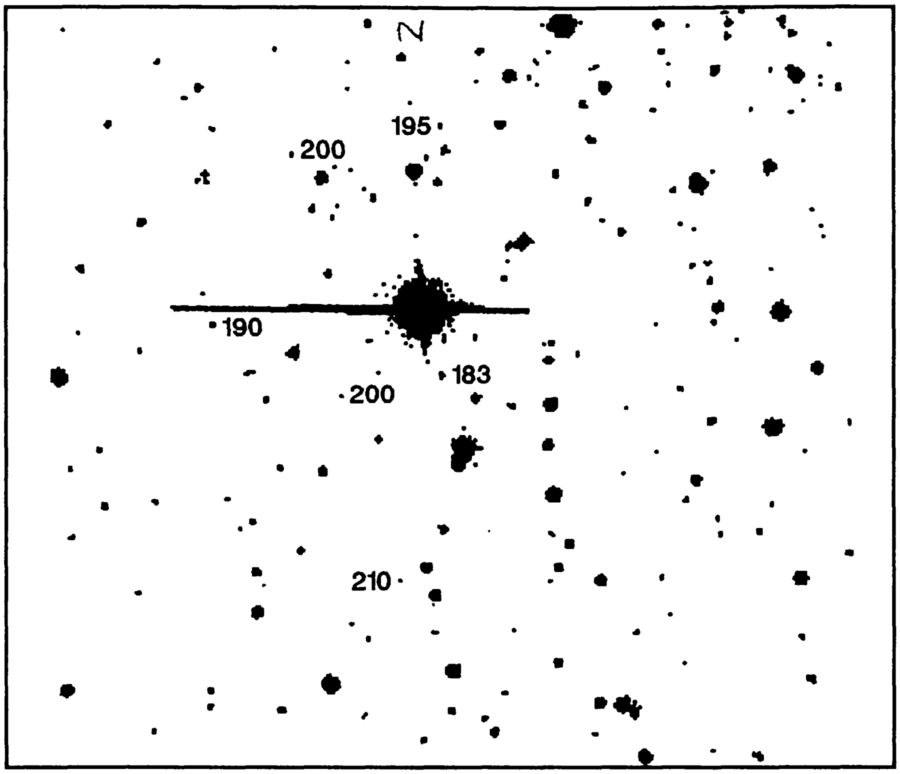

Figure 9. Detection of magnitude 21.0 in 600 seconds with a 6-inch f/3.3 Hyperbolic Astrograph from a dark site. The figure is 13 arc-minutes square.