Telescopes: The Tools of Astronomy

• Types of Telescopes
  – Optical
  – Radio
  – Infrared
  – Ultraviolet
  – High energy

• Imaging
  – Resolution
  – Interferometry
  – Image Processing

Hubble Space Telescope
Telescopes can be designed to gather visible and invisible radiation.
Telescopes: "light buckets"

Primary functions:
1. **Gather light** from a given region of sky.
2. **Focus** light.

Secondary functions:
1. **Resolve detail** in image
2. **Magnify** angular size of objects.
Optical Telescopes

• Designed to collect wavelengths of light that are visible to the human eye.

• Data observed by human eyes or recorded on photographs or in computers.
Astronomical Instruments: The Human Eye

First “telescope” used to observe and study heavens.
The Human Eye: Shortcomings

• Eye has limited size.
  – limited light gathering power.

• Eye has limited frequency response.
  – only detects E-M radiation in visible wavelengths.

• Eye distinguishes new image multiple times/second.
  – cannot be used to accumulate light over long period to intensify faint image.

• Eye cannot store image for future reference.
  – unlike photographic plate or CCD.
Optical Telescope Design

• Hans Lippershey, a Dutch spectacle maker, is credited for making the principles of the optical telescope widely known in early 1600s.

• Basic telescope has two parts:

  1. **Objective**
     
     Function: to **gather light**
     
     Materials: **lens/mirror** of longer focal length & larger diameter than the eyepiece

  2. **Eyepiece**
     
     Function: to **magnify image** made by objective
     
     Material: **lens** with a shorter focal length than the objective
Types of Optical Telescopes

• **Refractors**
  – Focus light with *refraction*: bend light path in transparent medium
  – Use lenses
  – First kind made
  – Kind used by Galileo

• **Reflectors**
  – Focus light by *reflection*: bounce light off a solid medium
  – Use mirrors
  – First designed and created by Sir Isaac Newton
  – Many different designs

• **Catadioptric**
  - Uses both lenses and mirrors (e.g., Schmidt-Cassegrain)
First Optical Telescopes: Refractors

Image of source is formed on focal plane and magnified by eyepiece.
The Yerkes 40” Refracting Telescope
Refractors: Disadvantages

• Quality optics require high tolerance
  – all lens surfaces must be perfect
  – glass will absorb light, especially IR and UV.
  – changes in orientation, temperature may flex lenses
  – large size very heavy, hard to support

• Chromatic aberration
  – light passes through glass
  – refraction a function of wavelength
  – all wavelengths focus different distances from lens
  – correctable with compound lenses
  – expensive to correct
Reflecting Telescopes
Reflecting Telescopes: Designs

Prime

Newtonian

Cassegrain

Coude
Why four designs?

• Prime focus
  – good for very faint objects
  – shorter focal length, less magnification

• Newtonian
  – least expensive amateur telescope

• Cassegrain
  – secondary mirror convex
  – increases focal length of objective mirror

• Coude
  – allows image to be in same position, independent to motion of telescope
  – often used in research with heavy detectors
Why build reflectors instead of refractors?

1. Mirrors don’t have chromatic aberration.
2. Mirrors don’t absorb light (especially infrared and UV).
3. Mirrors can be supported by their edge and back; lenses by ONLY their edge.
4. Mirrors have only one surface to be machined correctly; lenses have two.
5. Telescopes made with mirrors can be compact in design; reflectors cannot.
6. Telescopes using mirrors can have larger objective ends (because they have bigger mirrors), which means more light-gathering power.
Anglo-Australian Observatory

AAT 1

4-m reflector

© Anglo-Australian Observatory
Large Single-Mirror Reflectors

Largest single telescope mirror is the 6-meter telescope in Russia.

The Hale Telescope on Mt. Palomar is a 5-meter telescope.
Lowell Observatory’s 72” Perkins Telescope
2.1 m (82") Otto Struve Telescope
Texas Telescopes

McDonald Observatory near Ft. Davis, Texas is run by the University of Texas has a 2.7-meter telescope and many smaller ones. This observatory complex is one of the largest and most active in the world.

McDonald Observatory, 2.7-meter Smith Telescope

http://www.as.utexas.edu/mcdonald/mcdonald.html
New Telescope Designs

1. Multiple Mirror Telescopes
2. Light-weight Rigid Mirrors
3. Flexible Mirror Telescopes (active optics)
4. Segmented Mirror Telescopes
Keck Telescopes

Twin 10-m telescopes

Mauna Kea  13,700 ft elevation
Segmented Mirror Telescopes

- Mirror segments are fit together like a puzzle.
- Computers align the mirror segments.
- Keck and Keck II Telescopes are each 10 meters.
  - http://www2.keck.hawaii.edu:3636/

Hobby-Eberly Telescope
The World's Largest Optical Telescopes

• Interesting website with information about world’s largest optical telescopes: Optical Telescopes
Telescope Mountings

• Telescopes have special mountings that allow them to continue pointing at the same part of the sky as it appears to move overhead.
  – Equatorial mounting
    • telescope rotates about axis parallel to Earth’s rotational axis
    • compensates for Earth’s rotation
  – Other mountings that allow motion in altitude and azimuth are easier and cheaper to build, but more difficult to use.
    • Computers often used to keep the field of view centered by moving the telescope in two directions.
Powers of the Telescope

1. Magnifying Power
   The ability to enlarge an image.

2. Light Gathering Power
   The ability to see faint objects.

3. Resolving Power
   The ability to see fine details.
Magnifying Power

• Magnifying power is ability to enlarge image.
• A telescope forms a real image, but that image is not very large.
• The eyepiece lens is used to magnify the real image produced by the objective.
• A practical limit to magnifying power can be found:
  \[ 50 \times \text{diameter}_{\text{objective}} \text{ (inches)}. \]
• Normally, magnifying power is the least important for astronomers.
Magnification and Focal Length

Magnification = \frac{\text{focal length of objective}}{\text{focal length of eyepiece}}
• The objective’s area collects light.
• The larger the area, the greater the light-gathering power of telescope.

Light-gathering power proportional to \((\text{objective diameter})^2\).
Light Gathering Power

• Light gathering power affects the ability to see faint objects.
  • *Most* important power for most astronomers.

The human eye has an aperture of ~1/5"
and can see about 6,000 stars.
With a 2" telescope ~110,000 stars become visible.
Resolving Power

- Ability to see small details and sharp images.
- Objects that are so close together in sky that they blur together into single blob are easily seen as separate objects with a good telescope.
“Seeing” through the Atmosphere

**Seeing**: describes effects of atmospheric turbulence

- Individual photons from distant star strike detector in telescope at slightly different locations because of turbulence in Earth's atmosphere.
- Over time, individual photons cover a roughly circular region on detector, and even point-like image of a star is recorded as a small disk, called the **seeing disk**.
Closer to Sea Level, More air to pass through

atmosphere refracts starlight in random directions very quickly—stars “twinkle”.

multiple images created
Higher Altitude, telescopes in the high mountains

on mountain tops there is less atmosphere to look through—less distortion.
A Twinkle in Your Eye

• Why do stars appear to twinkle?

• Do planets twinkle?
  If so, why?
  If not, why not?
Blue light scatters more than red light. When the Sun is high in the sky you will see all of the colors if you look right at the Sun. But looking in other directions, you will see just the blue colors because some of the blue sunlight will be scattered back to you. When the Sun is near the horizon, the blue sunlight is scattered away leaving only the red and orange sunlight---the Sun appears red.
Site Selection

• Where are the best places for ground-based observatories?

• Important factors
  – dark/light pollution
  – good weather
  – dry air
  – air turbulence
Earth At Night
U.S.A. At Night (circa 1994-95)
Detection

• Collected light detected in many ways.
  – image observed and recorded
    • eye, photographic plate, CCD
  – measurements
    • intensity and time variability of source
      – photometer
    • spectrum of source
      – spectrometer
Imaging Devices

- The drawing what was seen through the telescope was the only way of recording images from the time of Galileo until about the middle of the 19th century.
- The first photograph taken through a telescope was in 1840.
- Photography greatly increased the "light gathering power" of the telescope by allowing an image to build up on the film.
- Electronic (digital) cameras utilizing CCD (charge-coupled device) chips have taken the place of film in many applications in the last few years.
  - CCD chips are much more sensitive over a wider spectral range than film and the digital images can be loaded directly into the computer and processed using special software.
Image Processing

• Computer processing of images can
  - reduce background noise
    • faint, unresolved sources
    • light scattered by atmosphere
    • electronic detector noise
  - compensate for known instrument defects
  - compensate for some atmospheric effects

Grnd-based  HST, 1990  Computer processed  HST, 1994
Laser-based Adaptive Optics

- Lasers probe the atmosphere for information about air turbulence.
- A computer modifies the mirror configuration 1000’s of times each second to compensate for atmospheric problems.
- Observations of the nearby double star Castor with and without adaptive optics.
- The two stars are separated by less than one arc second.
Radio Astronomy: Origins

• In the early 1930’s, Karl Jansky discovered that some of the interference affecting transatlantic radiotelephone transmissions was coming from a region in the sky that moved in the same way as the stars.

• These were radio emissions from the center of our galaxy.

• Grote Reber, amateur astronomer and professional radio technician, made the first map of the radio sky from a small radio telescope set up in his backyard in Illinois.
Radio Telescopes

• Much larger than reflecting optical telescopes
• Resemble satellite TV dishes
• Used to collect radio waves from space
• AM, FM, and TV signals interfere, so must be in a radio “protected” area

Radio telescopes most resemble what type of optical telescope?
Radio Astronomy: Wavelength Advantages

- NOT dependent on time of day/night
- NOT as dependent on weather
- Use of interferometry
- Gives different information than visible light
  - Quasars, pulsars
- Generally not absorbed while traveling space
  - pass through clouds of interstellar dust in our galactic plane
- Accuracy of dish shape not as hard to create or maintain
  - not need to be highly polish
  - often light weight
A RADIO SIGNAL MAP OF A RADIO OBJECT IN SPACE
• Collecting dish doesn’t need to be solid!
• “Tuned” to receive radio waves within a narrow range
• Re-tunable
• Need to have large dishes to obtain better angular resolution
  – radio wavelengths > 1cm
Arecibo Observatory: Largest Radio and Radar Dish

• 1000-ft radio dish
• used to
  – create maps of Moon, Venus, and Mars
  – discover pulsars and galaxies
  – measure the rotation rate of Mercury
  – discover planetary systems outside of our solar system
Very Large Array (VLA) in New Mexico

27 antennas, each 25 m in diameter

Effective diameter = 36 km

Yields radio-image details comparable to optical resolution
Neutral Hydrogen (21 cm) Sky

- First detected radio radiation of astronomical origin.
- ~3/4 of all interstellar gas is hydrogen.
- Neutral atomic hydrogen confined to flat layer.
Kitt Peak Observatory, Arizona

- The McMath-Pierce Solar Telescope is the largest solar instrument in the world.
- This is also the world's largest unobstructed aperture optical telescope, with a diameter of 1.6 meters.
McMath-Pierce Solar Telescope

- Includes a tower nearly 100 feet in height from which a shaft slants two hundred feet to the ground. The shaft continues into the mountain, forming an underground tunnel where the sun is viewed at the prime focus.
Sunspot study

- Two white light images of a sunspot, using different exposures, and obtained during exceptionally good seeing conditions at Kitt Peak.
Space Based Astronomy

• Every part of the electromagnetic spectrum is now observed.
• Due to the atmospheric window, some parts of the spectrum can only be observed from space.
• Due to the motions of the Earth’s atmosphere, some are best observed from above it.
Space Telescopes

Advantages to being in space:
1. Able to observe at all wavelengths of electromagnetic spectrum.
2. Increased resolving power because of almost perfect "seeing" in space.
3. Increased light gathering power because of extremely black background in space.
4. Can observe almost continuously.

For more information/list of space telescopes:

Orbital Telescopes
Wavelength Windows in Earth’s Atmosphere

- **Ozone and ordinary oxygen in atmosphere block completely**
- **Visible “window”**
- **Infrared “window”**
- **Water and carbon dioxide in atmosphere block nearly completely**
- **Radio “window”**
- **Electric charges in upper atmosphere block completely**

**X-rays**
- Short wavelengths
- Ultraviolet radiation absorbed by ozone in upper atmosphere
- X-rays absorbed

**Ozone layer**
- Visible light passes through atmosphere
- Infrared mostly absorbed by water vapor and carbon dioxide

**Optical telescope**
- **Radio waves**
-Radio telescope
Infrared Astronomy

• Almost entirely obscured by Earth’s atmosphere.
• Requires extreme coolant and cooling system due to infrared (heat) energy produced by the telescope itself.
• Telescope looks a lot like an optical one: uses mirrors and detectors sensitive to specific wavelength range investigated.
• Used to “see through” dust.
Infrared Telescopes

- Infrared wavelengths: $10^{-9}$ m to $10^{-3}$ m
- Shortest are at long wavelength end of photographic and CCD detection ability.
  - for $\lambda < 10^{-6}$m use optical style telescopes
  - for $\lambda > 10^{-6}$m use crystals with heat sensitive electrical resistance (e.g., germanium)
- Background noise:
  - $T_{\text{Earth}} = 300\,\text{K}$
  - Wien’s Law: $\lambda_{\text{max}} = \frac{3,000,000}{T} \times 10^{-9}\,\text{m}$
  - $\lambda_{\text{max}}(300\,\text{K}) = 10^{-5}\,\text{m}$
- Must shield detectors from heat, water vapor.
View of the Earth in Infrared
SIRTF
Space InfraRed Telescope Facility

- Launched Date: July 2002
- Estimated Lifetime: 2.5 years (minimum)
  5+ years (goal)
- Orbit: Earth-trailing, Heliocentric
- Wavelength Coverage: 3 - 180 microns
- Telescope: 85 cm diameter (33.5 Inches), f/12 lightweight Beryllium,
  cooled to less 5.5 K
- Diffraction Limit: 6.5 microns
- Science Capabilities:
  - Imaging / Photometry, 3-180 microns
  - Spectroscopy, 5-40 microns
  - Spectrophotometry, 50-100 microns
- Planetary Tracking: 1 arcsec / sec
- Cryogen / Volume: Liquid Helium / 360 liters (95 Gallons)
- Launch Mass: 950 kg (2094 lb)
This engineering image is a quick look at the sky through the Infrared Array Camera (IRAC).

The 5’ x 5’ image was taken in a low Galactic latitude region in the constellation Perseus. It results from 100 seconds of exposure time with the short-wavelength (3.6 micron) array.

(credit: NASA/JPL-Caltech)
Hubble Space Telescope

- Launched from the Space Shuttle in 1990.
- Largest telescope in space: 2.4 meter mirror.
- Mirror has an optical flaw (spherical aberration).
- Hubble was fixed by astronauts in 1994.
- Hubble has higher resolution and gathers more light than most Earth-based telescopes.
HST’s View of the Universe
UV Astronomy

• “Short” wavelength side of visible spectrum.
  – Almost entirely obscured by Earth’s atmosphere.

• Observations done via space telescope, balloons, and rockets.

• Used to see “new” star formation.
Extreme UV Telescope

Wavelengths: 400 nm to ~2-3 nm
Atmosphere opaque below 300 nm

*International Ultraviolet Explorer*
1978-1996

*Extreme UV Explorer*
lunched 1992, studied interstellar space near Sun
Far Ultraviolet Spectroscopic Explorer: FUSE

- Uses four mirror segments
  - two silicon carbonide coated to reflect short UV
  - two Al and Li fluoride coated to reflect longer UV
- Light from each mirror dispersed by four gratings
- Optical wavelength sensor (FES) provides visible wavelength pictures of the field of view.
X-ray Astronomy

• High energy/short wavelength end of spectrum.
  – Entirely obscured by Earth’s atmosphere.
• Look little like optical telescopes.
• Used in black-hole research, among others.
Chandra X-Ray Observatory

Orbits the Earth
200x higher than HST
or
1/3 of way to Moon
X-ray Imaging

- X-ray telescopes and medical x-rays are similar
  - source = x-ray machine or distant object
  - absorber = bones or gas cloud
  - detector = film or Chandra
Detecting X-rays

- Very high energy radiation
- At normal incidence, X-ray photons slam into mirrors as bullets slam into walls.
- But at grazing angles, X-rays will ricochet off mirror like bullets grazing a wall.
- Mirrors must be almost parallel to incoming X-rays; designed like barrels.
Chandra’s Mirrors

- Mirrors coated with iridium
- Smoothest and cleanest mirrors made to date
Observations of X-rays from the Lunar Surface

Chandra and the Moon
Gamma Ray Astronomy

• Highest energy photons.
  – Entirely obscured by Earth’s atmosphere.

• Utilizes different detection equipment to capture photons.
  High energy photons less abundant; hard to detect, hard to focus & measure

• Used to study the nuclei of galaxies and possible black hole; neutron star mergers.
Compton Gamma Ray Observatory (CGRO)

- Operated from 1991 to 2000
- Created all-sky map in gamma ray frequencies
  - pulsars and blazars
- 3 methods of detection
  - partial or total absorption of $\gamma$-ray energy within high density medium (large crystal of sodium iodide)
  - collimation using heavy absorbing materials to block out sky and create a small field of view
  - conversion process from $\gamma$-rays to electron-positron pairs in a spark chamber
All-Sky Map from CGRO

- Galactic plane energy from cosmic rays interacting with interstellar material.
- Bright spots on right side are pulsars Vela (supernova remnant), Geminga, Crab
- Bright spot above plane is a blazar 3C279
Why do we observe the universe in many wavelengths?
Our Sun in Different Wavelengths

X-Ray (Yohkoh)  Ultraviolet (SOHO)  Visible (BBSO)

Infrared (NSO)  Radio (Nobeyama)
Different Wavelengths

- By observing the Sun in different parts of the spectrum, we can get information about the different layers in the Sun's atmosphere.
  - X-ray images show us the structure of the hot corona, the outermost layer of the Sun. The brightest regions in the X-ray image are violent, high-temperature solar flares.
  - The ultraviolet image show additional regions of activity deeper in the Sun's atmosphere.
  - In visible light we see sunspots on the Sun's surface.
  - The infrared photo shows large, dark regions of cooler, denser gas where the infrared light is absorbed.
  - The radio image show us the middle layer of the Sun's atmosphere.
• The composite image above shows an ultraviolet view of the Sun (center) along with a visible light view of the Sun's corona.
• Combined images like this can show how features and events near the surface of the Sun are connected with the Sun's outer atmosphere.
Crab Nebula at Different Wavelengths

- x-ray
- far UV
- near UV
- visible
- infrared
- radio
Chapter 5

Telescopes
Tools of the Trade: Telescopes

• **Stars and other celestial objects are too far away to test directly**
  – Astronomers passively collect radiation emitted from distant objects
  – Extremely faint objects make collection of radiation difficult

• **Specialized Instruments Required**
  – Need to measure brightness, spectra, and positions with high precision
  – Astronomers use mirrored telescopes and observatories

• **Modern Astronomers are rarely at the eyepiece, more often they are at a computer terminal!**
The Powers of a Telescope

• Collecting Power
  – Bigger telescope, more light collected!

• Focusing Power
  – Use mirrors or lenses to bend the path of light rays to create images

• Resolving Power
  – Picking out the details in an image
Light Gathering Power

• Light collected proportional to “collector” area
  – Pupil for the eye
  – Mirror or lens for a telescope

• Telescope “funnels” light to our eyes for a brighter image

• Small changes in “collector” radius give large change in number of photons caught

• Telescopes described by lens or mirror diameter (inches)
Focusing Power

• Refraction
  – Light moving at an angle from one material to another will bend due to a process called *refraction*
  – Refraction occurs because the speed of light is different in different materials
Refraction

Light beam in air

Light on this side of beam is still in air and thus is not slowed yet.

Light on this side of beam enters medium first and is slowed, causing the beam to deflect.

Light beam in denser substance such as a glass of water

Fast walker

Slow walker
Refracting Telescopes

• A lens employs refraction to bend light
• Telescopes that employ lenses to collect and focus light are called refractors
Disadvantages to Refractors

• Lenses have many disadvantages in large telescopes!
  – Large lenses are extremely expensive to fabricate
  – A large lens will sag in the center since it can only be supported on the edges
  – Dispersion causes images to have colored fringes
  – Many lens materials absorb short-wavelength light
Reflecting Telescopes

• Reflectors
  – Used almost exclusively by astronomers today
  – Twin Keck telescopes, located on the 14,000 foot volcanic peak Mauna Kea in Hawaii, have 10-meter collector mirrors!
  – Light is focused in front of the mirror
Reflecting Telescopes

- A *secondary mirror* may be used to deflect the light to the side or through a hole in the *primary mirror*
- *Multi-mirror instruments* and *extremely thin mirrors* are two modern approaches to dealing with large pieces of glass in a telescope system
Styles of Refractors

Mount camera here. In very large telescopes, the observer may ride in a "cage" here!

Primary mirror

Prime focus

Secondary mirror

Cassegrain focus

Diagonal mirror

Newtonian focus
Resolving Power

- A telescope’s ability to discern detail is referred to as its **resolving power**
- Resolving power is limited by the wave nature of light through a phenomenon called **diffraction**

- Waves are diffracted as they pass through narrow openings
- A diffracted point source of light appears as a point surrounded by rings of light
Resolving Power and Aperture

• Two points of light separated by an angle $\alpha$ (in arcsec) can be seen at a wavelength $\lambda$ (in nm) only if the telescope diameter $D$ (in cm) satisfies:

$$D > 0.02 \frac{\lambda}{\alpha}$$
Increasing Resolving Power: Interferometers

- For a given wavelength, resolution is increased for a larger telescope diameter
- An interferometer accomplishes this by simultaneously combining observations from two or more widely-spaced telescopes
Interferometers

- The resolution is determined by the individual telescope separations and not the individual diameters of the telescopes themselves.
- Key to the process is the wave nature of interference and the electronic processing of the waves from the various telescopes.
Detecting the Light

• The Human Eye
  – Once used with a telescope to record observations or make sketches
  – Not good at detecting faint light, even with the 10-meter Keck telescopes

• Photographic Film
  – Chemically stores data to increase sensitivity to dim light
  – Very inefficient: Only 4% of striking photons recorded on film

• Electronic Detectors
  – Incoming photons strike an array of semiconductor pixels that are coupled to a computer
  – Efficiencies of 75% possible
  – **CCD** (Charged-coupled Device) for pictures
Nonvisible Wavelengths

- Many astronomical objects radiate in wavelengths other than visible:
  - Cold gas clouds radiate in the radio
  - Dust clouds radiate in the infrared
  - Hot gases around black holes emit x-rays
Radio Observatories
Radio Observations

- False color images are typically used to depict wavelength distributions in non-visible observations.
Major Space Observatories

Why put them in space?

- Hubble Space Telescope (13.6 m long) – HST
- Extreme Ultraviolet Explorer – EUVE
- Spitzer Infrared Space Telescope
- Chandra X-ray Telescope Satellite
Space vs. Ground-Based Observatories

- **Space-Based Advantages**
  - Freedom from atmospheric blurring
  - Freedom of atmospheric absorption

- **Ground-Based Advantages**
  - Larger collecting power
  - Equipment easily fixed

- **Ground-Based Considerations**
  - Weather, humidity, and haze
  - Light pollution
Observatories

• The immense telescopes and their associated equipment require observatories to facilitate their use and protection from the elements.

• Thousands of observatories are scattered throughout the world and are on every continent including Antarctica.

• Some observatories:
  – Twin 10-meter Keck telescopes are largest in U.S.
  – Largest optical telescope, VLT (Very Large Telescope) in Chile, is an array of four 8-meter mirrors.
Going Observing

• To observe at a major observatory, an astronomer must:
  – Submit a proposal to a committee that allocates telescope time
  – If given observing time, assure all necessary equipment and materials will be available
  – Be prepared to observe at various hours of the day

• Astronomers may also “observe” via the Internet
  – Large data archives now exist for investigations covering certain wavelengths sometimes for the entire sky
  – Archives help better prepare astronomers for onsite observations at an observatory
Computers and Astronomy

• For many astronomers, operating a computer and being able to program are more important than knowing how to use a telescope

• Computers accomplish several tasks:
  – Solve equations
  – Move telescopes and feed information to detectors
  – Convert data into useful form
  – Networks for communication and data exchange
Scintillation

- Refraction is also responsible for *seeing*
  - Twinkling of stars
  - AKA *Scintillation*

- Temperature and density differences in pockets of air shift the image of the star

Wind moves pockets of slightly cooler air across your line of sight.

Light ray shifted from side to side by refraction in air pockets.
Atmospheric Blurring

- Twinkling of stars in sky, called **scintillation**, is caused by moving atmospheric irregularities refracting star light into a blend of paths to the eye.
- The condition of the sky for viewing is referred to as the **seeing**.
- Distorted seeing can be improved by **adaptive optics**, which employs a powerful laser and correcting mirrors to offset scintillation.
Light Pollution

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.