Variable Star Search
Using ROTSE3 Data

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Outline

- Celestial Coordinates
- CCDs
- HR Diagram
- ROTSE
- ROTSE3
- Variable Stars
- Binary Stars
- Eclipsing Binary Stars
- Contact Binary Stars
- Light Curves
- Conclusion
- References

V838 Monocerotis and light echo
CCD History

- Invented by William S. Boyle & George E. Smith at AT&T Bell Labs, 1969 -- awarded 2009 Nobel Prize for Physics

- Working version produced within a year

- Light sensitive properties were quickly exploited for imaging applications -- major revolution in Astronomy

- Improved the light gathering power of telescopes by almost two orders of magnitude

- CCDs are present in every instrument which uses electronic imaging -- TV, video systems, digital cameras, optical scanners

The Tadpole Galaxy (UGC 10214; Arp 188). The "narrow filament", which appears to be tidal feature caused by a gravitational interaction, can be seen extending across this image.
<table>
<thead>
<tr>
<th></th>
<th>FILM</th>
<th>CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of reaction</strong></td>
<td>Chemical, physical</td>
<td>Physical</td>
</tr>
<tr>
<td><strong>Quantum Efficiency</strong></td>
<td>&lt;10%</td>
<td>&gt;80%</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>10 to 25 micron</td>
<td>6 to 24 micron</td>
</tr>
<tr>
<td><strong>Pixel matrix size</strong></td>
<td>1200x1800 (24x36 format)</td>
<td>512x512 to 8192x8192</td>
</tr>
<tr>
<td><strong>Spectral response</strong></td>
<td>350 to 650 nm can be extended from 250 to 950 nm</td>
<td>400 to 900 nm can be extended from 300 to 1100 nm</td>
</tr>
<tr>
<td><strong>Time from the end of the exposure to image</strong></td>
<td>&gt;30 minutes</td>
<td>&lt; 10 seconds (for larger format CCD)</td>
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<tr>
<td><strong>Dynamic range</strong></td>
<td>&lt;16 bits</td>
<td>&gt;=16 bits (65536 gray levels)</td>
</tr>
<tr>
<td><strong>Equipment cost</strong></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Auto guiding when exposing</strong></td>
<td>Not possible</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Direct image processing</strong></td>
<td>Only after scanning the image</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Remotely image acquisition</strong></td>
<td>Not possible</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Automatic image capturing (no need for operator)</strong></td>
<td>Not possible</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Need for cooling system</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Special chemical and physical processes and procedures for sensitivity increment</strong></td>
<td>Yes</td>
<td>No need</td>
</tr>
<tr>
<td><strong>Special environment for developing</strong></td>
<td>Yes</td>
<td>No</td>
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<tr>
<td><strong>Interferometric telescope connection capability</strong></td>
<td>Not possible</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Automatic correction on adaptive and active optics capability</strong></td>
<td>Not possible</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Automatic protection against saturation</strong></td>
<td>Not possible</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Antiblooming capability</strong></td>
<td>Not possible</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Reciprocity effect failure</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Loss of sensitivity if not cooled</strong></td>
<td>Yes but low</td>
<td>Yes but high</td>
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<tr>
<td><strong>Binning capability</strong></td>
<td>Only after scanning the image</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Resolution increasing</strong></td>
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<td>Yes</td>
</tr>
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</table>
Photoelectric Effect

\[ K = hf - W \] (\( W \) = work function -- minimum energy required to remove an electron from the surface of any given metal)

An image is acquired when incident light in the form of photons falls on the array of pixels.

The energy associated with each photon is absorbed by the silicon and a reaction takes place that creates an electron-hole charge pair.

The number of electrons collected at each pixel is linearly dependent on light level and exposure time, nonlinearly dependent on wavelength.
Semiconductors

Intermediate conductivity between insulators & conductors

Small energy input can promote e- to conduction band

Silicon band gap = 1.12 eV; $\lambda = 1$ μm (NIF)
CCD Basic Principles

- CCD: charge-couple device
- Array of linked (“coupled”) capacitors
- Photons interact in a semiconductor substrate, electrons released
- Applied electric field collects & stores the electrons in pixels
- Pixels are coupled and can transfer their charges to neighboring pixels
- Stored charge is transferred to an output amplifier and read out, stored on a computer as an image file

The charge packets (electrons, blue) are collected in potential wells (yellow) created by applying positive voltage at the gate electrodes (G). Applying positive voltage to the gate electrode in the correct sequence transfers the charge packets.
In order to produce an image, a CCD must accomplish 4 functions:

- Generate photoelectrons (rain drops)
- Collect electrons (buckets)
- Transfer the collected charges (conveyor belts)
- Read the charges (weighing stations)
Photoelectric interaction of photon with Si atoms generates electron-hole pairs

- $\text{Ne} = \frac{E}{W}$ (on average)
- $\text{Ne} =$ number of electrons, $E =$ energy of photon
- $W \approx 3.7 \text{ eV/e}$ (temperature dependent)

Incident photons create a charge cloud which can diffuse and/or move under influence of an electric field.
Charge collection

A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD

Buried channel CCD MOS plus pn junction Prevents trapping by surface states at the semiconductor-oxide interface

Fig. 6.7. A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD.

Fig. 6.12. (a) A single storage site in the buried-channel type of CCD. As the gate voltage increases the depleted zones finally meet.
Electrostatic Potential in CCD

Figure 1.19 Buried-channel potential well. Janesick, 2001
As charge is integrated and stored in the pixel architecture, there must be a means of getting the charge to the sense amplifier -- physically separated from the pixels

As the charge associated with one pixel moves, the charge in all the pixels associated with that row or column moves simultaneously

Charge packets are eventually shifted to the output sense node -- electrons are converted to voltage (charge-to-voltage amplifier)
• Charge readout
  - Rapid transfer to framestore region; a)→b)
  - Slower line-by-line transfer to serial register; b)→c)
  - Charge in each pixel measured by amplifier (the slower the measurement, the lower the noise)
  - Chandra ACIS: 100 kHz readout produces a 3.2 second frametime
Energy Resolution

Spectral Range

FI: front illuminated
BN: back illuminated, no coating
DD: deep depletion
Quantum efficiency (ratio of output electrons to input photons) : >50%; >80% for certain wavelengths

Graphs: quantum efficiency as a function of wavelength for several types of CCDs

Large domain of wavelengths for the spectral response of CCDs
Experimental Applications

- **Particle Physics**
  - Track detectors (ionization)
  - Vertex detector at International Linear Collider (ILC)
  - In-situ Storage Image Sensor (ISIS)

- **Astrophysics**
  - Hubble Space Telescope (ACS)
  - Chandra X-ray Observatory
  - XMM-Newton X-ray Observatory
  - Sloan Digital Sky Survey
  - ROTSE

*Array of 30 CCDs used on Sloan Digital Sky Survey telescope imaging camera, an example of "drift-scanning."*
Summary

Advantages
- Good spatial resolution
- High quantum efficiency
- Large spectral window
- High dynamic range
- High photometric precision
- Good linearity
- Reliable rigidity

Disadvantages
- Limited in size
- Thin depletion area (20-40 μm): small # of electron-hole pairs per ionizing particle
- Thermal noise (dark current) -- requires cooling
- Noise due to cosmic rays
- Blooming
- Slow readout

Vertical smear: If the shifting is not fast enough, errors can result from light that falls on a cell holding charge during the transfer. These errors are referred to as "vertical smear" and cause a strong light source to create a vertical line above and below its exact location.
HR Diagram

- 20th century telescopes determined the apparent brightness of many stars
- Combined with the distances to nearby stars obtained from parallax, absolute magnitude (luminosity) of nearby stars could be inferred from inverse square law
- Ejnar Hertzsprung (1873-1967) & Henry Russell (1877-1957) plotted absolute magnitude against surface temp (1905-1915) to create HR diagram
- Used to define different types of stars & to match theoretical predictions of stellar evolution using computer models with observations of actual stars
- Used to determine distance of stars too far away for trigonometric parallax:
  - Measure apparent magnitude
  - Spectroscopy yields surface temp, hence luminosity (absolute mag)
  - Calculate distance
- Effective to \( \approx 300 \) kly; beyond that stars are too faint to be measured accurately
ROTSE

- ROTSE: Robotic Optical Transient Search Experiment
- Primary goal: Observations in optical light of GRBs
- Observation and detection of optical transients on time scales of seconds to days
- Also used for variable star searches, identification of other transient events (AGNs, supernovae, flare stars, X-ray binaries, SGRs)

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ROTSE

- **ROTSE1:**
  - Initiated in 1998
  - Four CCD cameras w/ telephoto lenses
  - FOV: $16^\circ \times 16^\circ$
  - Limiting magnitude: 14-15
  - Observed 1st optical counterpart to GRB in progress on 01/23/99
  - Retired from active operation

- **ROTSE3:**
  - Initiated in 2003
  - Four 0.45 m robotic reflecting telescopes
  - Managed, fully automated, Linux environment
  - Greater sensitivity than ROTSE1
  - f-ratio: 1.9
  - Limiting magnitude: 19-20
  - FOV: $1.85^\circ \times 1.85^\circ$
DATA:
- ROTSE3 file GRB040408
- 417 observations imaged over 4 hours
- RA: 272.24°, DEC: -20.40°
- Field located in Sagittarius (toward galactic center)

ANALYSIS:
- University of Michigan ROTSE IDL library, ported to SMU
- Examine raw images, drop poor ones
- Process & calibrate raw images
- Investigate time variation of optical light output for variable star candidates
- Photometry: Measurement of changes in brightness plotted to generate light curves
- Determine shape, period, amplitude
- Identify short period pulsating variable stars (δ Sct), or other variable types (eclipsing binary, contact binary)
ROTSE3: Target field in Sagittarius
Variable Stars

CLASSIFICATION OF VARIABLE STARS

GROUP

CLASS

TYPE

I. PULSATING STARS

Cepheids
RR Lyrae
RV Tauri
Long-period variables

Type I Classical
Type II W Virginis

Mira type
Semiregular

VARIABLE STARS

INTRINSIC

II. ERUPTIVE (Cataclysmic stars)

Supernovae
Novae
Recurrent novae
Dwarf novae
Symbiotic stars
R Coronae Borealis

EXTRINSIC

III. ECLIPSING BINARIES

IV. ROTATING VARIABLES

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Pulsating Variable Stars: δ Scuti

- Low amplitude pulsating variables (dwarf Cepheids)
- Some have amplitudes of about one magnitude & regular light curves
  - Radial pulsations
  - One dominant pulsation mode
- Others have complex light curves & multiple periods with smaller light variations
  - Radial & non-radial pulsations
  - May have multiple modes of oscillation
- Reside near instability strip of HR diagram
- Importance:
  - Asteroseismology: Pulsations used to study interior structure
  - Standard candles (higher amplitude)
Binary Stars

- Classified into 4 types by the method in which they are observed:
  - Visual: By observation of double stars (may or may not be gravitationally bound; Example: Mizar)
  - Astrometric: By measuring a deviation in a star's position caused by an unseen companion (wobble about a point in space)
  - Photometric: By changes in brightness due to an eclipse
  - Spectroscopic: By periodic changes in spectral lines (Doppler effect – small separation between stars, high orbital velocity)

- Best method available to determine the mass of a distant star:
  - Orbit around their common center of mass
  - Mass of individual stars determined using Kepler’s laws & Newton’s law of universal gravitation
  - Establishes relationship between a star’s temperature, radius, & mass
  - Allows for the determination of the mass of non-binaries

- Large proportion of stars exist in binary systems (estimated 1/3 of stars in Milky Way)
  - Binaries important to our understanding of the processes by which stars form
  - Period and mass of the binary components reveal amount of angular momentum in the system
  - Provide important clues about the conditions under which the stars were formed
Eclipsing Binary Stars

Eclipsing Binary Star

Light Curve

Magnitude

Time

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Contact Binary Stars (*W Ursae Majoris* variables)

- Almost all known contact binary systems are also eclipsing
- Constitute about 1% of all stars
- Spectral class: F, G, K
- Component stars are so close that they are in physical contact
- Roche lobes: Region of space around a star in a binary system within which orbiting material is gravitationally bound to that star
- Roche lobes are filled for contact binaries; surrounds both stars, shared by both
- Typical lifetime of millions to billions of years
- As friction of the envelope brakes the orbital motion, stars may eventually merge -- Chandrasekhar limit (supernova)
Contact Binary Stars: Algol (β Persei)
Candidate Contact Binary Star

object = 12437, Designation: ROTSE3 J180829.56--203048.7

object = 14150, Designation: ROTSE3 J180829.49--203048.1

object = 15087, Designation: ROTSE3 J180829.49--203048.5

object = 1329, Designation: ROTSE3 J180829.57--203048.9
Period: 0.38130  Max. Mag: 15.43  Min. Mag: 14.83
Conclusion: Discovery

- **VSX J180829.4-203047**
  - Type: EW
  - Period: 0.3813 d
  - Amplitude: 0.636
  - Discoverers:
    - Farley Ferrante (SMU)
    - Weikang Zheng (Michigan)
    - Govinda Dhungana (SMU)
    - Robert Kehoe (SMU)

- 3 additional discoveries:
  - VSX J154029.8+453200
  - VSX J161803.4+420417
  - VSX J162221.9+412340

- More to come…

- And supernovae too…

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"You're in the right place and this is the right time, but I'm afraid you're in the wrong alternate universe."

AS THE UNIVERSE CONTINUED TO CONTRACT...

"I'll tell you what's beyond the observable universe - lots and lots of unobservable universe."
Intermission

"I think you should be more explicit here in Step Two."

\[ (a+b)^n \]

\[ = (a+b)^n \]

\[ = \text{etc.} \]
Intermission

3. Find x.

Here it is

A proton approaches a long line of positive charge so that with it’s initial trajectory it would intersect the line. The line has a uniform charge density of 5 nanoC/m. If the proton starts off with velocity 300 km/s a distance 1 km from the line charge, what is the distance of closest approach?

- Mass of proton=1.67E-27 kg
- K=8.99E9 Nnm/CC
- Hint: find the field and potential that affect the proton.

Problem
Use calculus to find the identity of Batman.

\[
U = 3(q_1q_2)/r = 147.15
\]

\[
U_s = 1/2(100)x^2 = 50x^2
\]

No, there is an elephant in the way.
Standard Candles: Distance Measurement in Astronomy

Farley V. Ferrante
Southern Methodist University
OUTLINE

- Cosmic Distance Ladder
- Standard Candles
  - Parallax
  - Cepheid variables
  - Planetary nebula
  - Most luminous supergiants
  - Most luminous globular clusters
  - Most luminous H II regions
  - Supernovae
  - Hubble constant & red shifts

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The Cosmic Distance Ladder

- Distances far too vast to be measured directly
- Several methods of indirect measurement
- Clever methods relying on careful observation and basic mathematics
- Cosmic distance ladder: A progression of indirect methods which scale, overlap, & calibrate parameters for large distances in terms of smaller distances
- More methods calibrate these distances until distances that can be measured directly are achieved
The Cosmic Distance Ladder

**Parallax to nearby stars**

- **3.26 ly**: Alpha Centauri
- **32.6 ly**: Pleiades cluster
- **326 ly**: Parallax (Hipparcos) out to 150 pc
- **326 kly**: Population II RR Lyrae variables 5 to 100 kpc
- **326 Mly**: Spectroscopic parallax 40 pc to 10 kpc
- **3260 Mly**: Population I Cepheid variables 1 kpc to 30 Mpc

- **3.26 kly**: Center of our Galaxy
- **32.6 kly**: Large Magellanic Cloud
- **326 kly**: Tully-Fisher 700 kpc to 150 Mpc
- **326 Mly**: Virgo cluster
- **3260 Mly**: Coma cluster

**~500 ly**
The Cosmic Distance Ladder

Spectroscopic parallax to stars in galaxy ~30,000 ly
The Cosmic Distance Ladder

Calibrated variable stars in galaxy ~50,000 ly
The Cosmic Distance Ladder

Calibrated variable stars, supernovae in 'nearby' galaxies ~10 Mly

- 3.26 ly (1 pc)
- 32.6 ly (10 pc)
- 326 ly (100 pc)
- 3.26 kly (1 kpc)
- 32.6 kly (10 kpc)
- 326 kly (100 kpc)
- 3.26 Mly (1 Mpc)
- 32.6 Mly (10 Mpc)
- 326 Mly (100 Mpc)
- 3260 Mly (1000 Mpc)

- Alpha Centauri
- Pleiades cluster
- Center of our Galaxy
- Large Magellanic Cloud
- M31
- Virgo cluster
- Coma cluster

- Population II RR Lyrae variables 5 to 100 kpc
- Spectroscopic parallax 40 pc to 10 kpc
- Population I Cepheid variables 1 kpc to 30 Mpc
- Type Ia supernovae 1 to over 1000 Mpc
- Tully-Fisher 700 kpc to 150 Mpc
The Cosmic Distance Ladder

Calibrated variable stars, supernovae, most massive galaxies in ‘distant’ clusters

~500 Mly to 5 Gly
The Cosmic Distance Ladder

**Hubble’s Law**

- 3.26 ly, 1 pc
- 32.6 ly, 10 pc
- 326 ly, 100 pc
- 3.26 kly, 1 kpc
- 32.6 kly, 10 kpc
- 326 kly, 100 kpc
- 3.26 Mly, 1 Mpc
- 32.6 Mly, 10 Mpc
- 326 Mly, 100 Mpc
- 3260 Mly, 1000 Mpc

**~10 Gly**

- M31, Virgo cluster
- Type Ia supernovae 1 to over 1000 Mpc
- Tully-Fisher 700 kpc to 150 Mpc
- Population I Cepheid variables 1 kpc to 30 Mpc
- Population II RR Lyrae variables 5 to 100 kpc
- Spectroscopic parallax 40 pc to 10 kpc
- Parallax (Hipparcos) out to 150 pc
- Center of our Galaxy – Large Magellanic Cloud
- Pleiades cluster
- Alpha Centauri
• Magnitude: Historical unit (Hipparchus) of stellar brightness such that 5 magnitudes represents a factor of 100 in intensity

• Apparent magnitude: Number assigned to visual brightness of an object; originally a scale of 1-6

• Absolute magnitude: Magnitude an object would have at 10 pc – convenient distance for comparison

• **List of most luminous stars**
Parallax

- Distance Units:
  - 1 AU = 1.49597870700 x $10^{11}$ m
  - 1 ly = 9.46 053 x $10^{15}$ m = 6.324 x $10^4$ AU
  - 1 pc = 3.085678 x $10^{16}$ m = 3.261633 ly = 206 264.81 AU

- 1 parsec (pc): Distance from the Sun to an astronomical object for which the parallax angle is one arcsecond.

- Stellar parallax: A nearby star's apparent movement against the background of more distant stars as the Earth revolves around the Sun.

- By taking measurements of the same star 6 months apart and comparing the angular deviation, distance to the star can be calculated.

- 1st performed by Friedrich Wilhelm Bessel (1838).

- Limit of measurement with Earth based telescopes is about 20 pc -- includes around 2000 stars.

  - Precision parallax measurements of 273 Cepheid variables, 2 of them not previously observed.
RR Lyrae Variables

- Short period variable stars (< 1 day)
- Commonly found in globular clusters
- Named after prototype RR Lyrae in Lyra
  - Consumed H at core
  - Evolved off of main sequence & passed through red giant stage
  - Fusion of He in core
- Pulsating horizontal branch stars
  - Spectral class A (F occasionally)
  - Mass ≈ 0.5 solar mass; originally about 0.8 solar mass but shed mass during evolution
- Pulse in a manner similar to Cepheids
  - Old, low mass, metal-poor, Population II stars
  - More common but less luminous than Cepheids
  - Absolute mag = 0.75 (40-50 times solar luminosity)
- Good standard candles for relatively near objects (within Milky Way)
- Also used in globular cluster studies & to study chemical properties of older stars
Cepheid Variables

- Cepheid variables (Population I stars) make good standard candles because:
  - Long period variables
  - Follow a well-defined period-luminosity relationship
  - Bright giants -- luminous enough to see at great distances

- Henrietta Swan Leavitt (1868-1921): Observed a certain class of stars that oscillated in brightness periodically
  - Plotting absolute brightness vs periodicity yielded a precise relationship
  - Provided another way to obtain absolute brightness, & hence observed distances
  - Because Cepheids are so bright, this method works up to 13 Mly
  - Most galaxies have at least one Cepheid in them, so distances to all galaxies out to a reasonably large distance can be determined

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Cepheid Variables

- δ Cephei

**Period - Luminosity Relationship**

- Type I (Classical) Cepheids
- Type II (W Virginis) Cepheids

**Delta Cephei**

*Julian Date vs. Magnitude*

<table>
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<tr>
<th>Julian Date</th>
<th>Magnitude</th>
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<td>2451380</td>
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Planetary Nebulae

- Planetary nebula luminosity function (PNLF) is a secondary distance indicator used in astronomy.
- Uses the [O III] $\lambda$5007 forbidden line found in all planetary nebula which are members of old stellar populations (Population II).
- Works well for both spiral and elliptical galaxies despite completely different stellar populations.
- Part of the Extragalactic Distance Scale.
Most Luminous Supergiants

- brightest supergiants in a given galaxy will have about the same absolute magnitudes:
  - About -8 for red supergiants
  - About -9 for blue supergiants

- These two types of supergiants can be seen out to about 50 Mly & 80 Mly respectively

- Compared to a maximum distance of about 20 Mly for Cepheid variables

Galactic center: Sgr A* is located near the center of this image. Most of these stars are very young and massive and heavily reddened. Spectroscopic studies indicate that the stars are luminous super giants and only a few 10s of millions years old.

VY Canis Majoris (Class M hypergiant): \(3 \times 10^5\) times solar luminosity; about 25 times solar mass.
Most Luminous Globular Clusters

- Beyond 80 Mly, even the brightest blue supergiants fade from view
- Must turn to entire star clusters & nebulae for luminosity measurement
- Brightest globular clusters have total luminosity of about magnitude -10 and can be observed out to 130 Mly

*The Messier 80 globular cluster in the constellation Scorpius is located about 28,000 ly from the Sun and contains hundreds of thousands of stars.*
H II Regions

- H II regions: Areas in space which are luminous with the emission spectrum of ionized

- Brightest H II regions have absolute magnitudes of $\approx -12$ & can be detected out to about 300 Mly

- Compared to $\approx 130$ Mly for the brightest globular clusters

- Associated with the presence of massive O-type & B-type stars
  - Surface temperatures in the range 15 000 – 60 000 K
  - Characteristic blackbody radiation curves peak in UV

- These stars will often be surrounded by vast clouds of H gas

- UV can ionize the H atoms:
  - H atoms tend to attract electrons & reassemble
  - Captured electrons cascading down through the quantum states of the H atom
  - Emit characteristic photons of light upon each downward jump

Eagle Nebula (M16): “The Pillars of Creation”
Supernovae (Sne)

- Beyond 300 Mly where even the brightest HII regions are indistinct, the only individual standard candles are supernovae which can reach a peak magnitude $= -19$

- In theory, such magnitudes should be visible to 8 Gly

- However, supernovae types Ib, Ic & II show large brightness variations; intervening matter absorbs light

- Supernova classified as Type 1a are of great usefulness
  - Provide a distance measurement uncertainty approaching 5% over vast distance ranges of $\approx 1000$ Mpc

*Nearby Supernova in Whirpool Galaxy (M51)*
Edwin Hubble (1889-1953) formulated the law relating velocity (as observed by red shift) with distance:

- Led in turn to the famous “Big Bang” model of the expanding universe.

\[ v = H_0 D \]

- Combined existing data against more precise red-shift measurements & known speed of light
- Hubble’s law can then be used to give another measurement of distance at the largest scales
- These measurements have led to accurate maps of the universe at very large scales
  - Led to many discoveries of very large-scale structures not otherwise possible
  - Ex: Great Wall, Great Attractor, etc.
- Hubble constant:
  - Particle Data Group "best modern value" of the Hubble constant: \( H_0 = 72 \) km/s per Mpc (± 10%).
  - Comes from the use of type Ia supernovae (which give relative distances to about 5%) along with data from Cepheid variables gathered by the HST
  - WMAP mission data Hubble constant:
    - \( H_0 = 71.0 \) 2.5 km/s per Mpc
Hubble Constant & Red Shifts

Age of Universe = $1/H_0 = 13.75 \pm 0.11 \text{ Gy}$
References

- AAVSO: www.aavso.org
- Astronomy Magazine: www.astronomy.com
- Hyperphysics: http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html
- Introduction to CCDs (PowerPoint), Simon Tulloch (2007)
- McDonald Observatory: http://mcdonaldobservatory.org/
- ROTSE: www.rotse.net
- SIMBAD Astronomical Database: http://simbad.u-strasbg.fr/simbad/
- The CCD Detector (PowerPoint), Sami Dib, Jean Surdej (2006)
- Theory and Observation of Pulsating Stars: http://www.univie.ac.at/tops