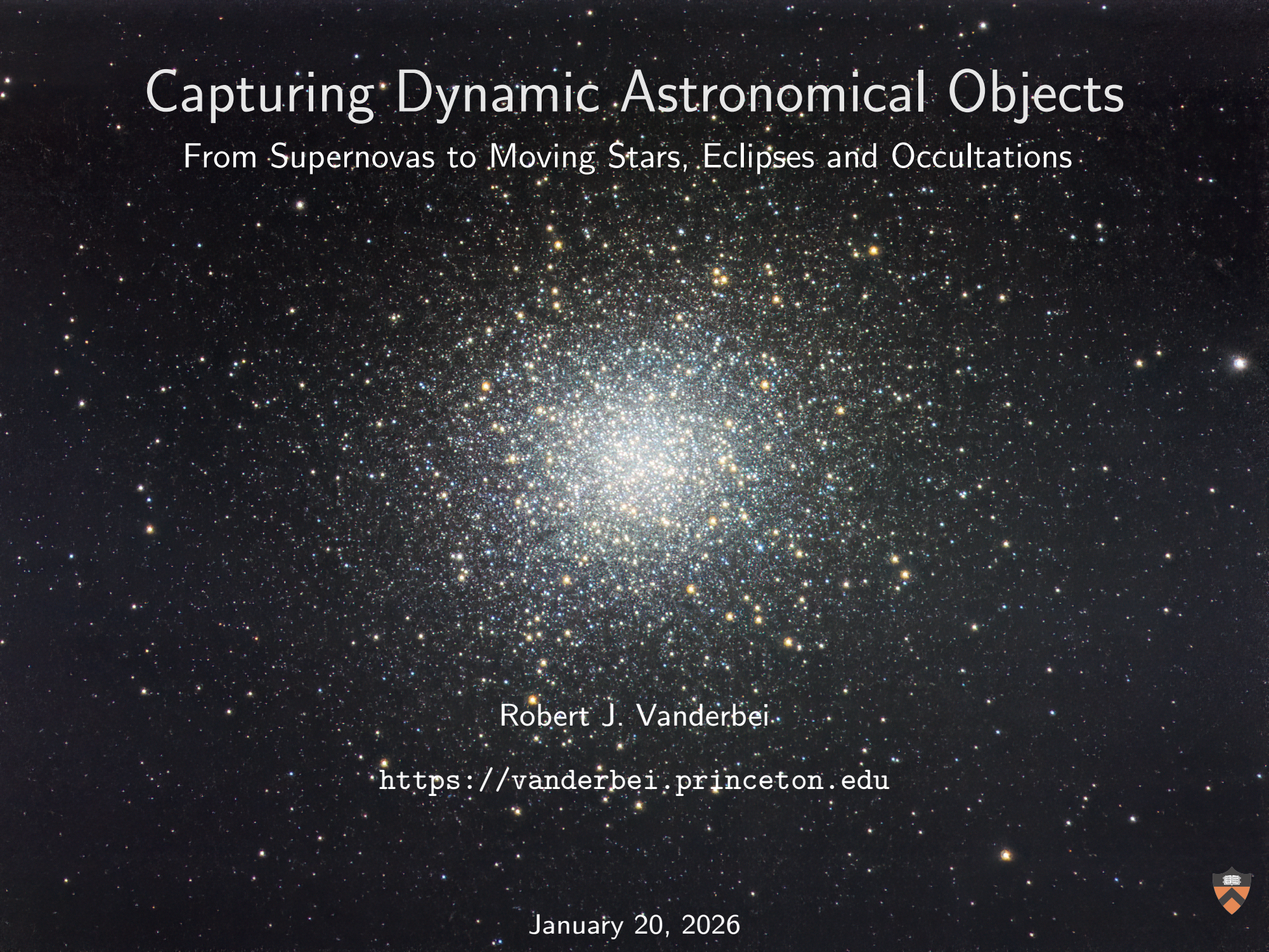
Capturing Dynamic Astronomical Objects

From Supernovas to Moving Stars, Eclipses and Occultations



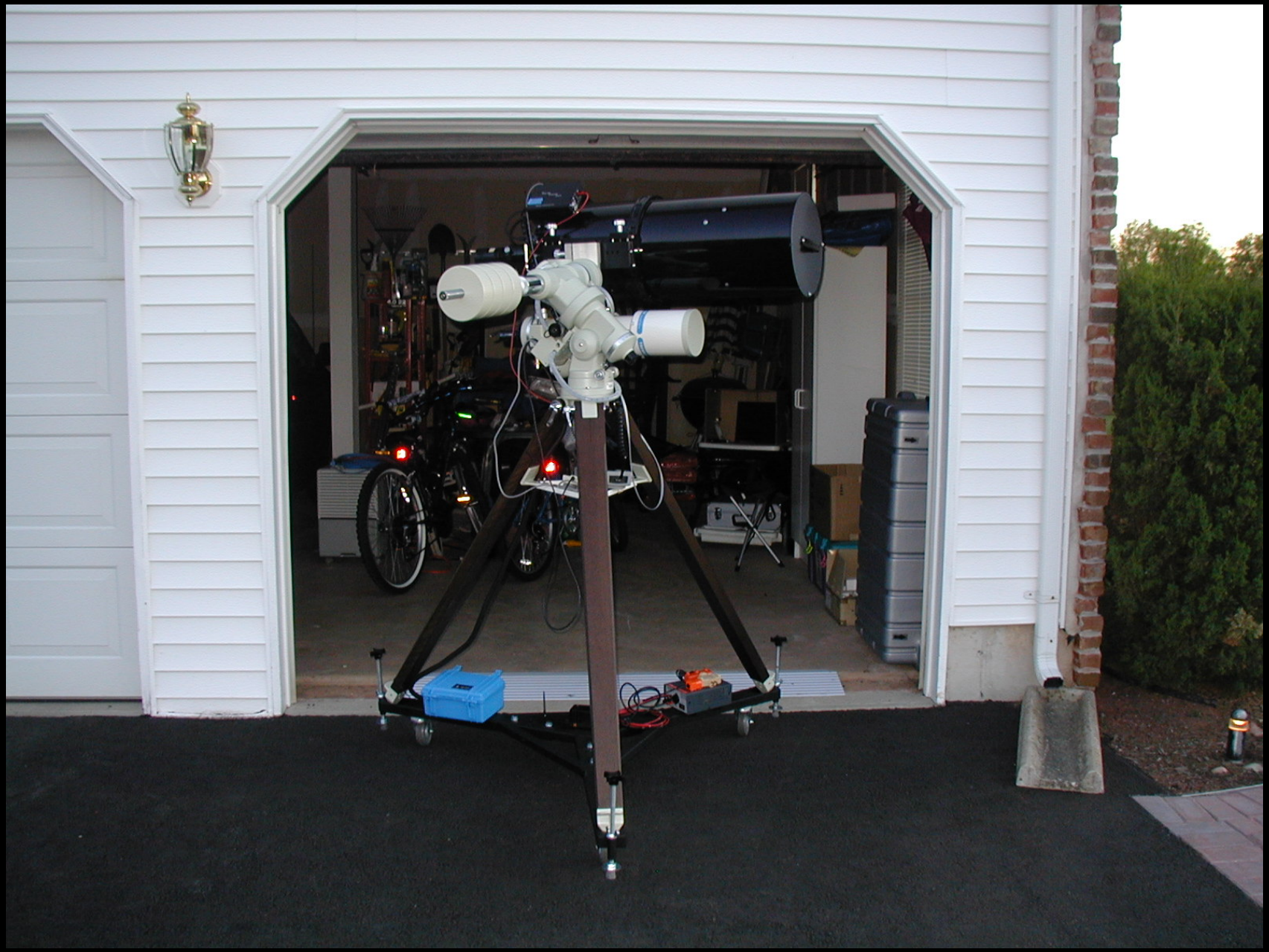
Robert J. Vanderbei

https://vanderbei.princeton.edu

January 20, 2026

Me and My Telescopes

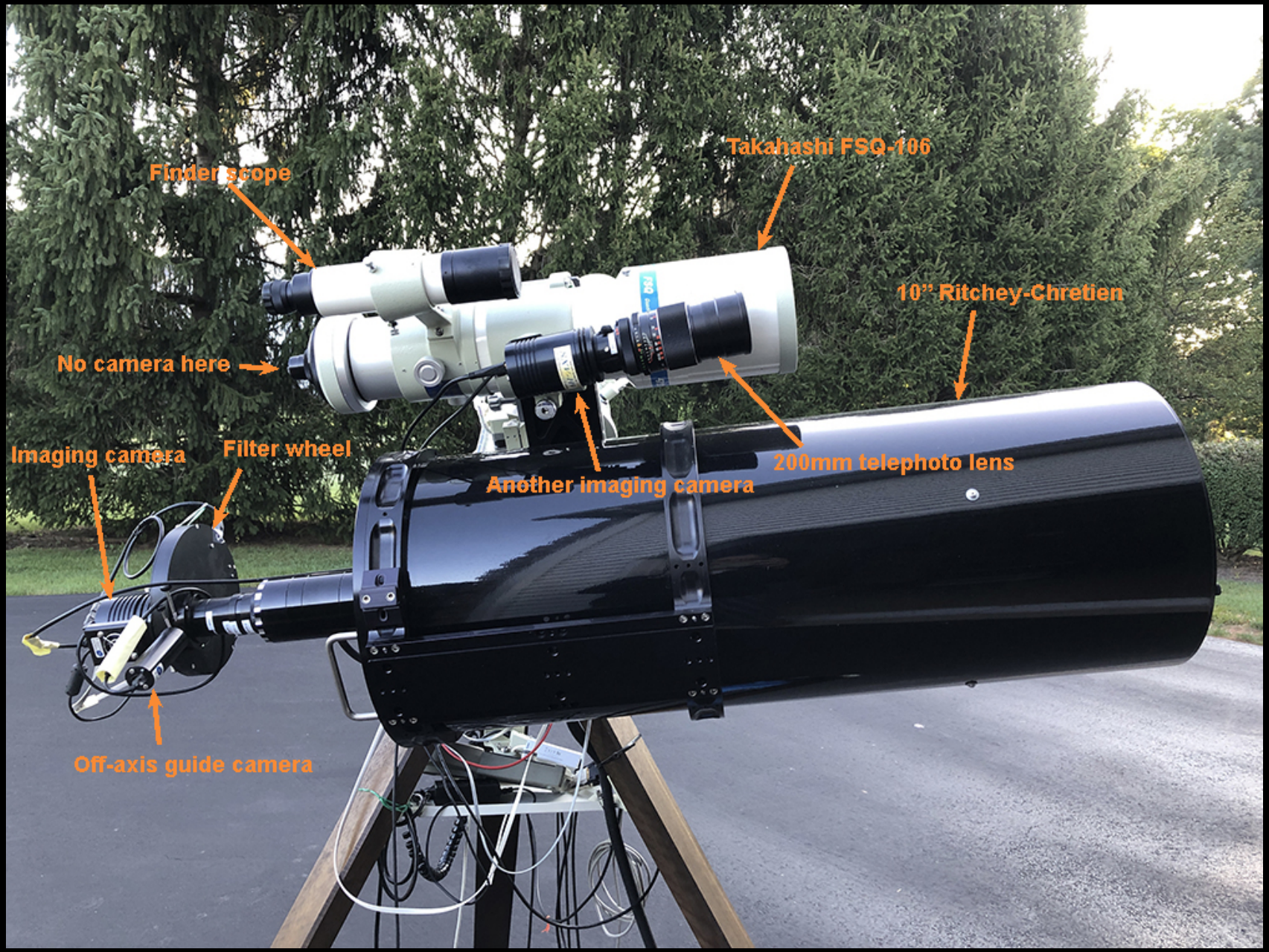
Move equipment outside.



Earth Rotates

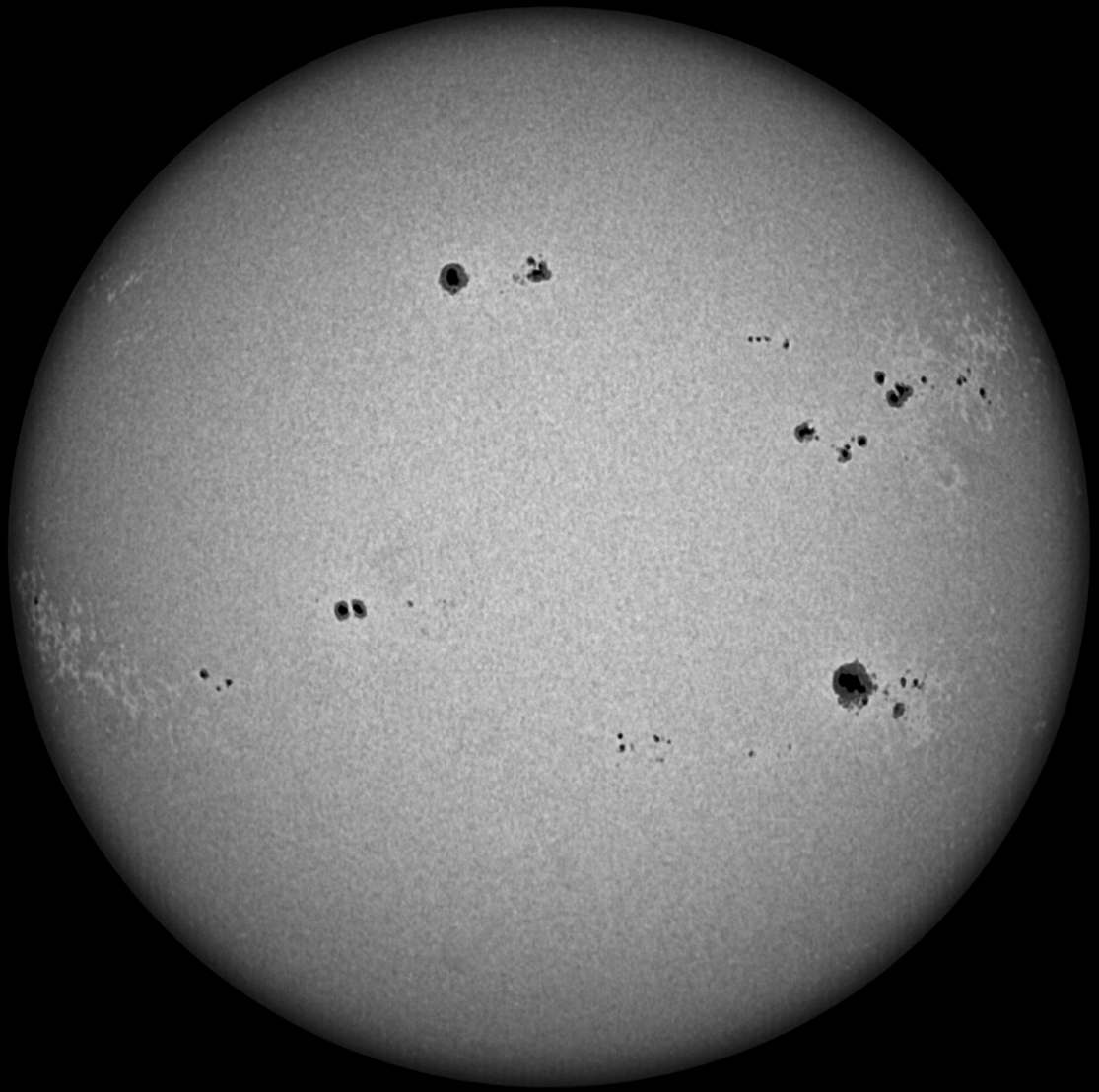
Ready To Go...

10” Reflector, 4” Refractor, Telephoto Lens



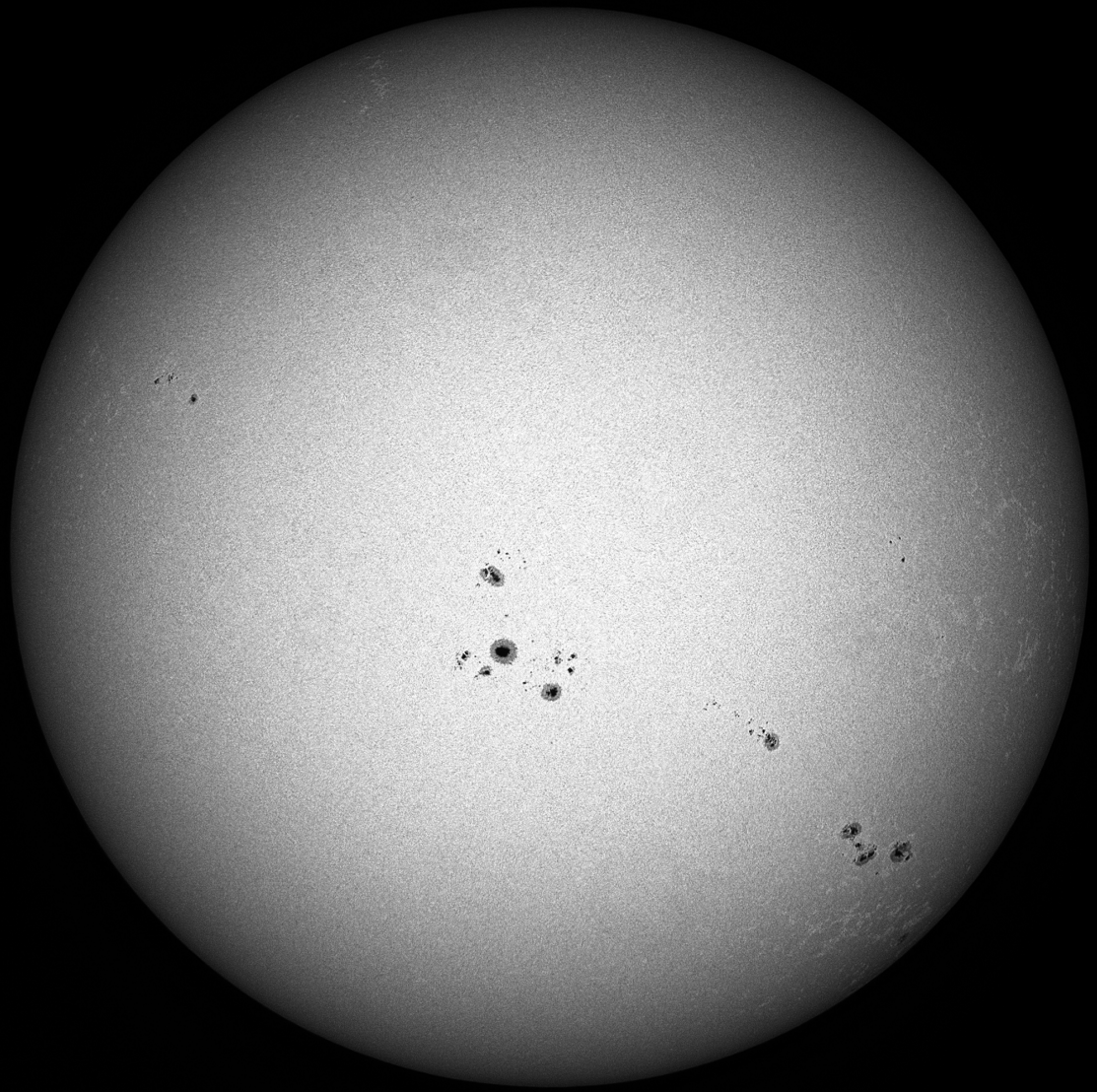
Sun has Sunspots

Jan 16, 2023



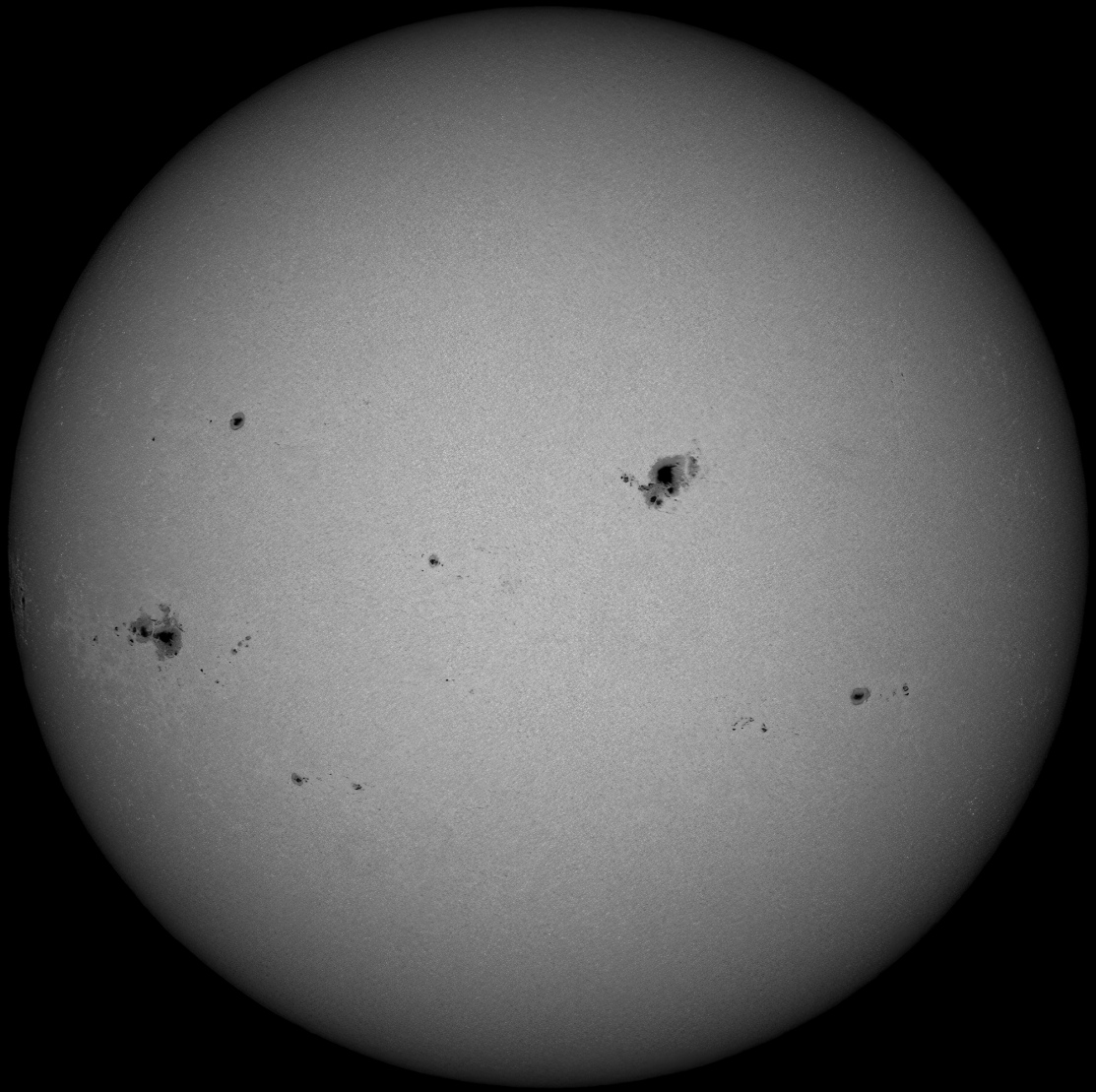
Sun has Sunspots

May 22, 2024

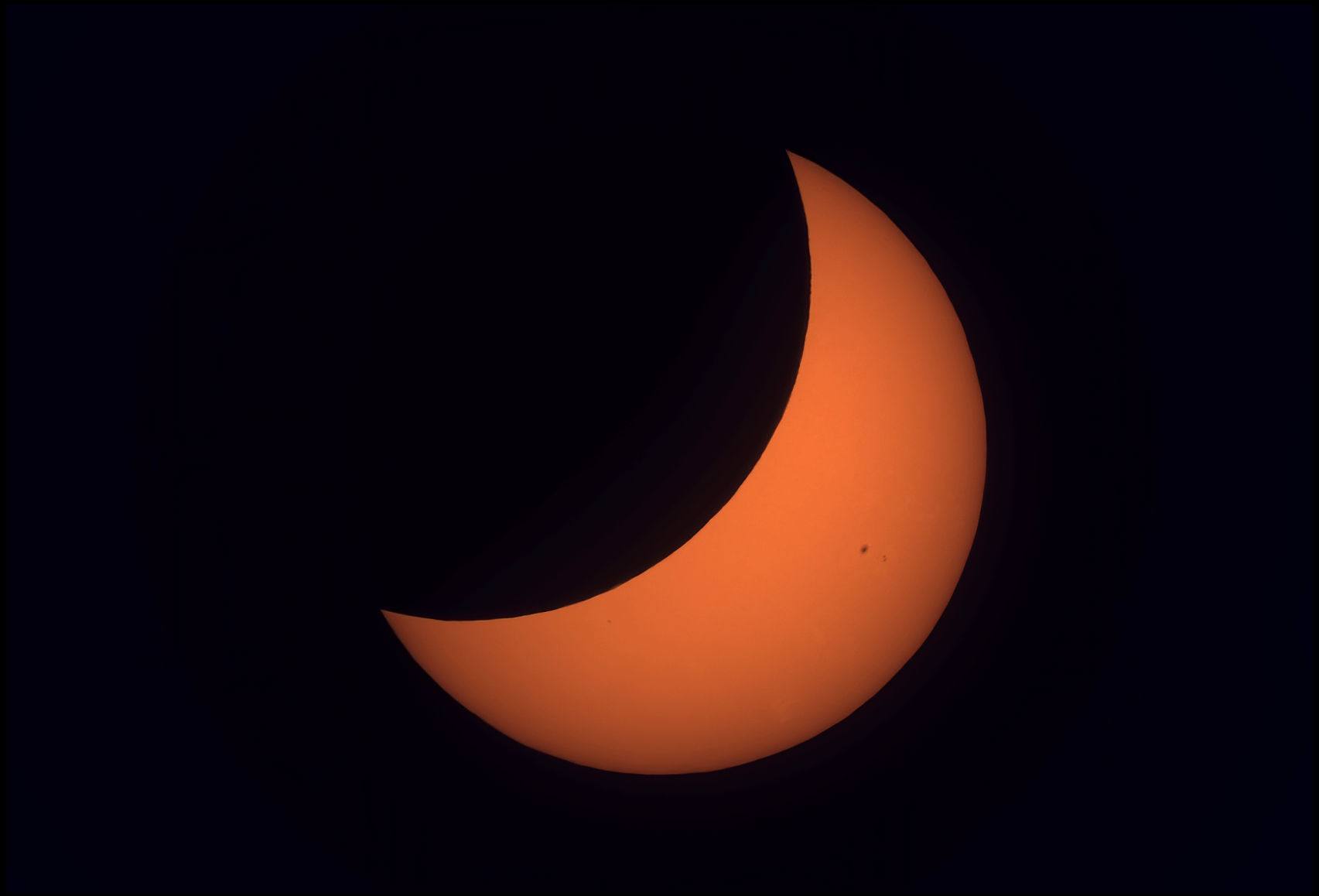


Sun has Sunspots

Aug 13, 2024



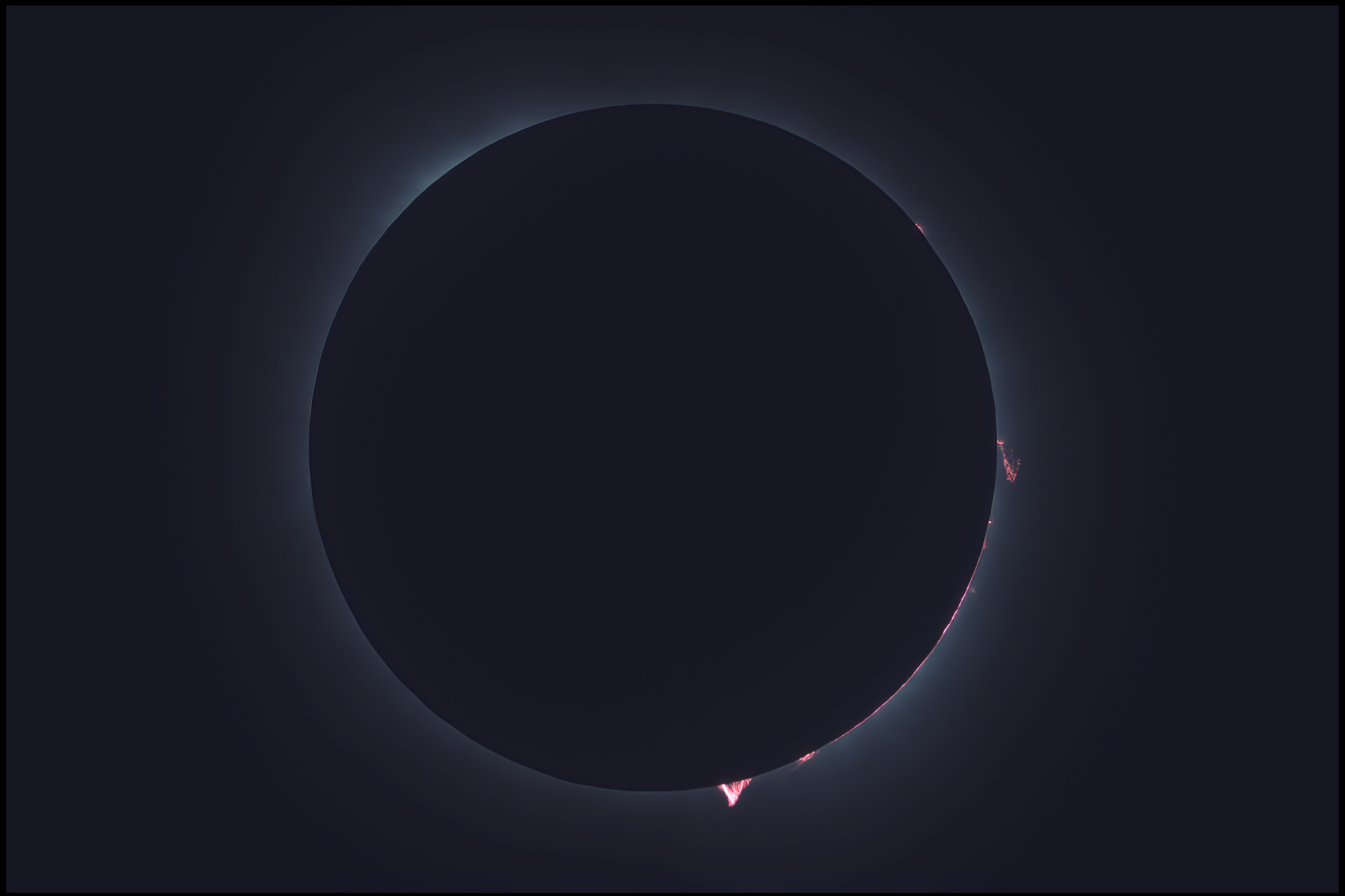
Solar Eclipse: Partial Phases – 2024



Solar Eclipse: Jet Stream

Video taken by Aram Friedman

Solar Eclipse: Totality – 2024



Crescent Moon

Crescent Moon

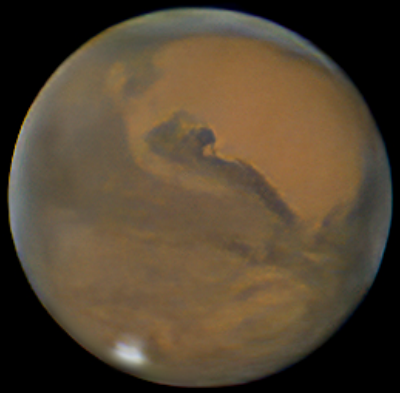
Crescent Moon

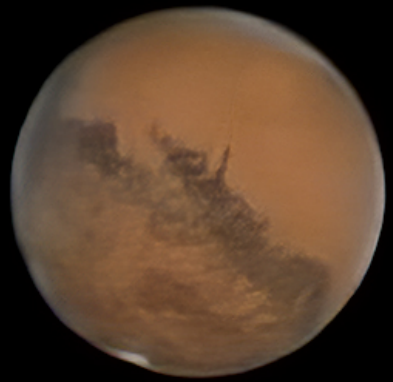
Full Moon

1.2 sec

Mars

Oct. 6 and 18, 2020



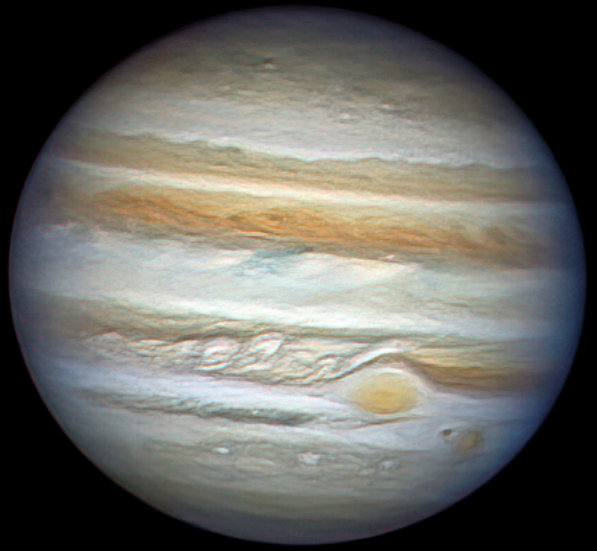


Moon and Mars

Jan. 13, 2025

Jupiter and Saturn

32 and 67 min



Comet 103P / Double Cluster

1.2 min / 7460 and 7640 yrs

Comet 103P / Double Cluster

55 minutes in 10 seconds

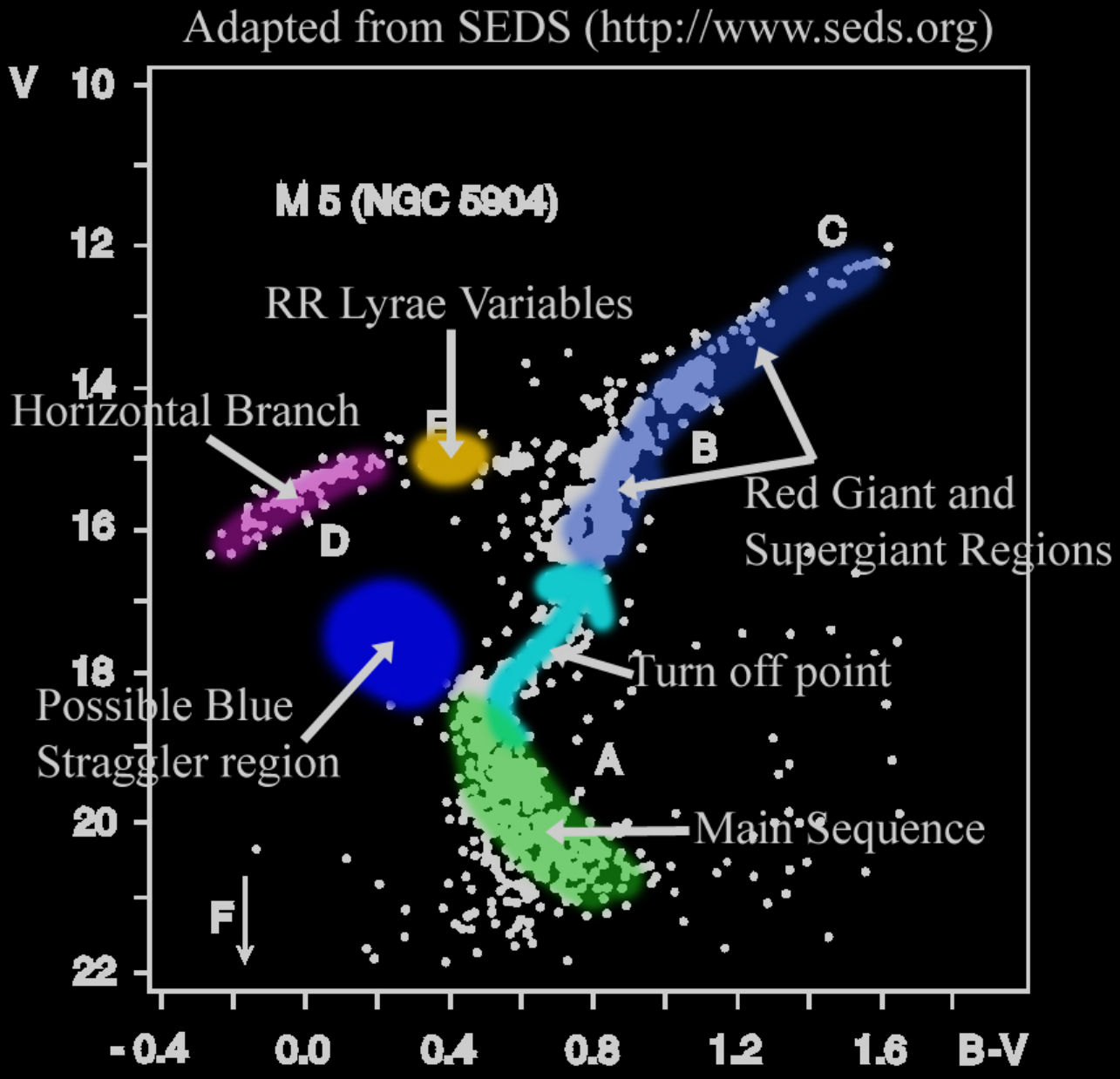
Comet Tsuchinshan 7:17 pm, Oct. 15 2024 4.1 min

Aurora Borealis (aka Northern Lights)

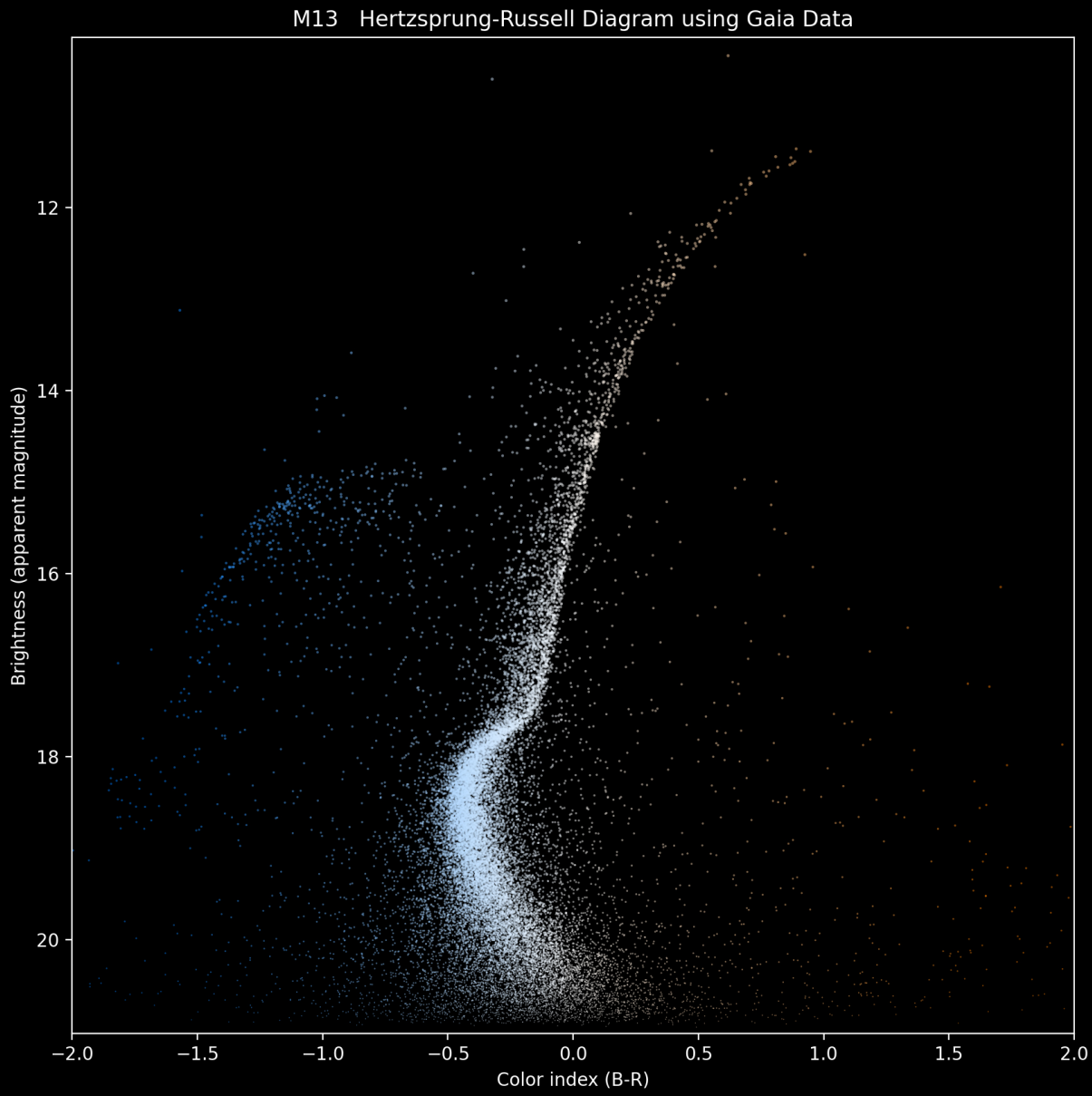
7:20pm, Oct. 11 2024

Looking Out Beyond Our Solar System

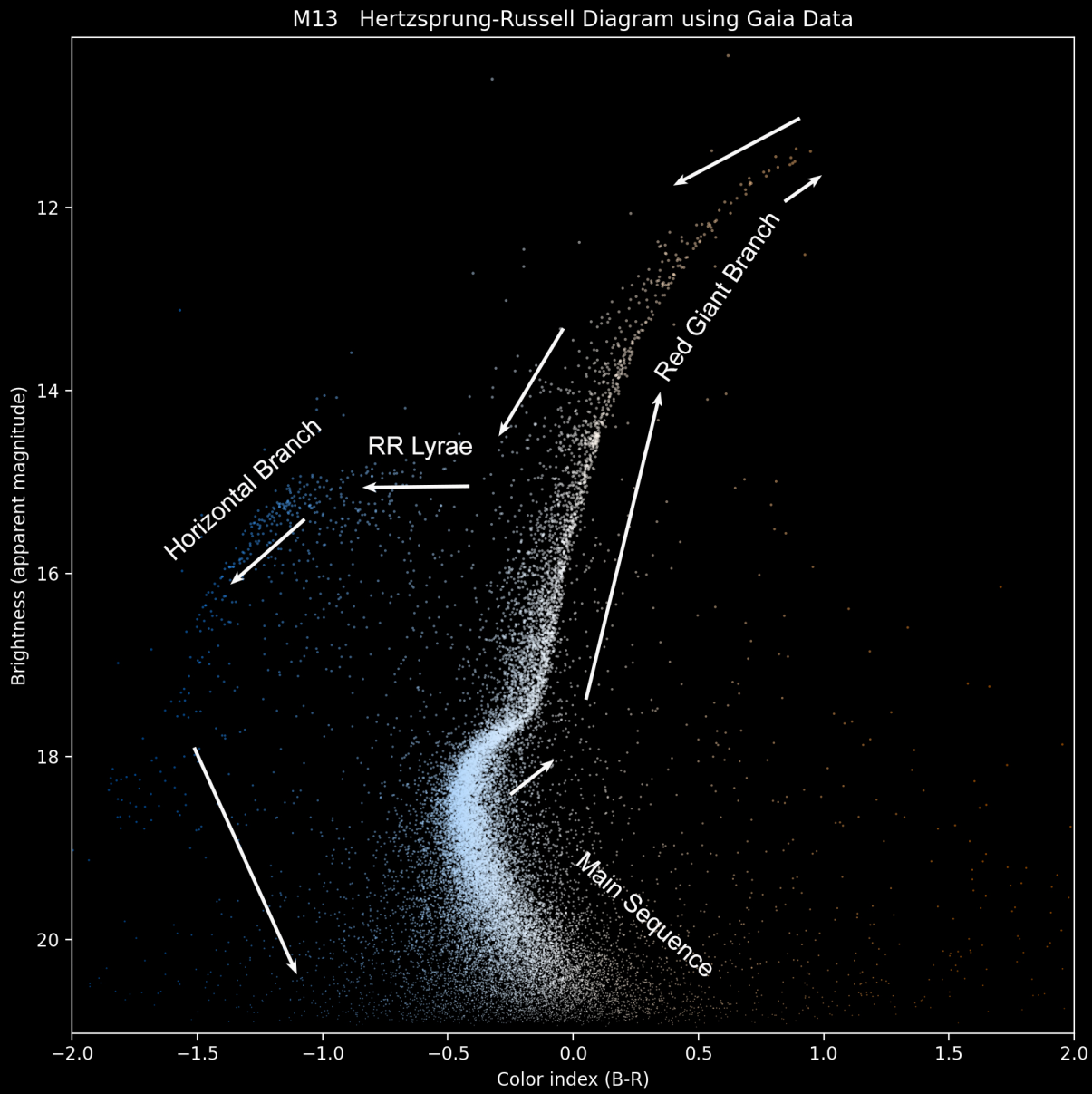
Variable Stars



HR-Diagram Using Gaia Data



HR-Diagram Using Gaia Data

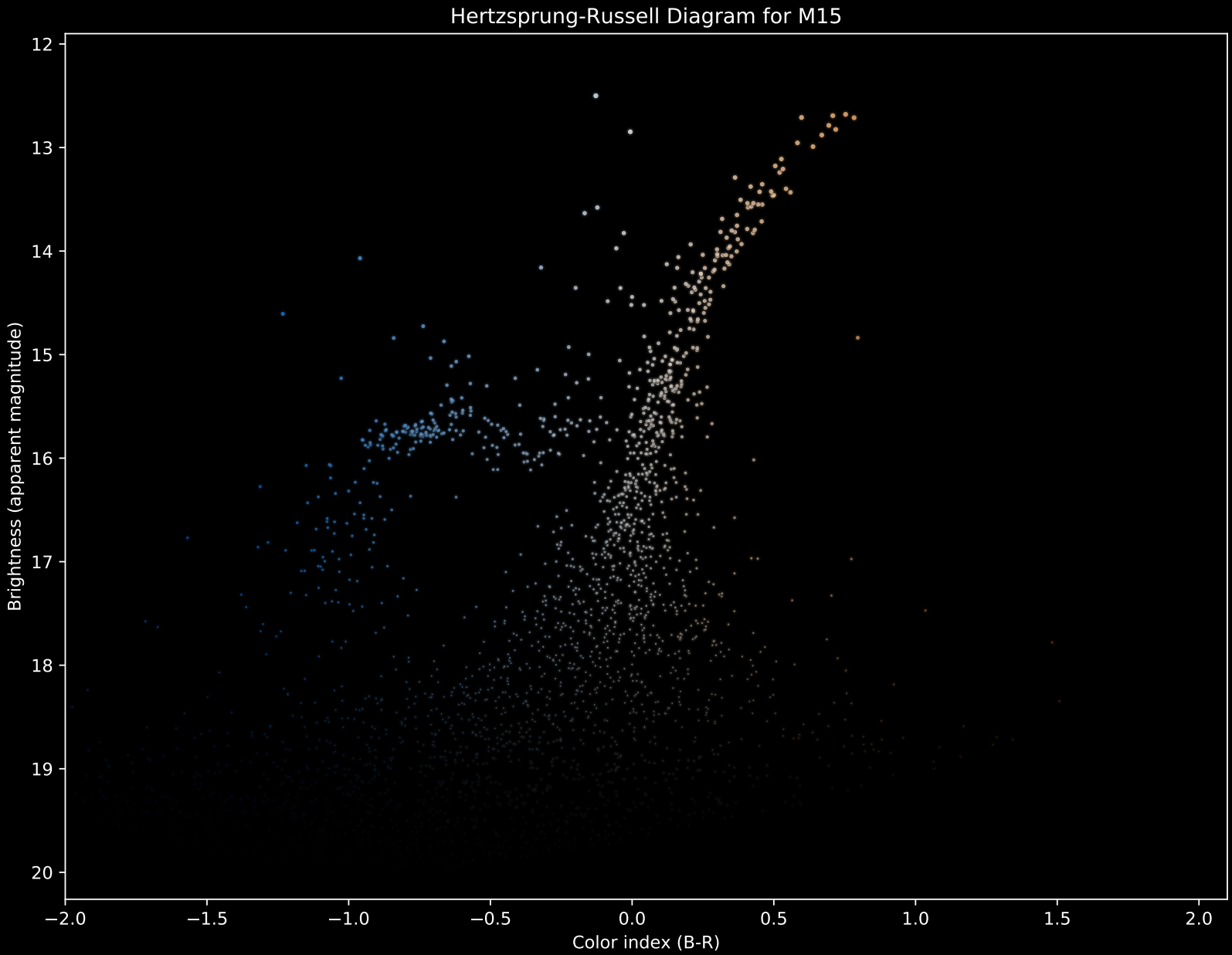


Globular Cluster M15

Click to see it

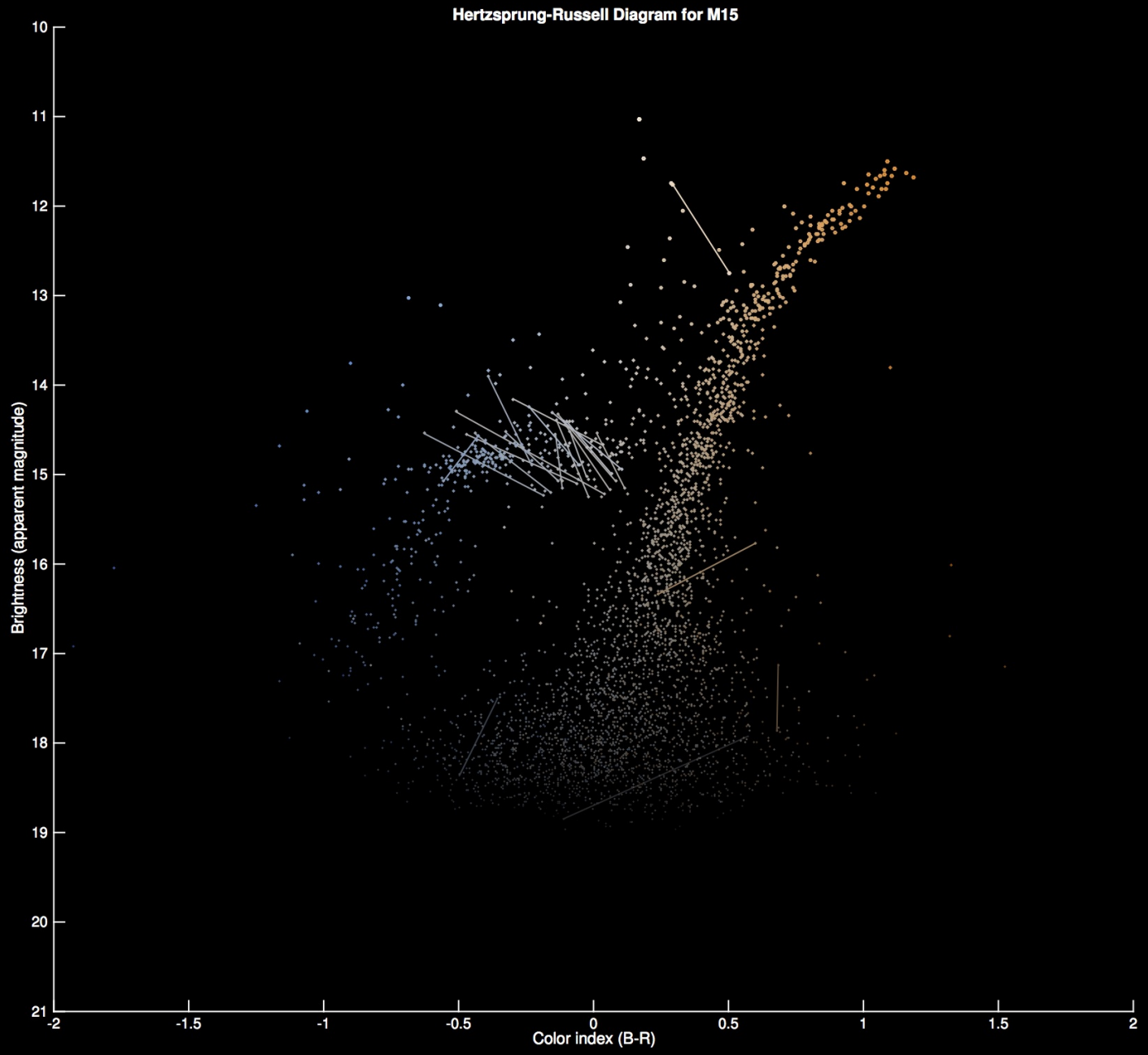
HR-Diagram for M15

Click to see it



HR-Diagram Showing RR-Lyrae Stars

Click to see it



RR-Lyrae distance: 258 parsecs

RR-Lyrae distance: 258 parsecs

Dumbbell Nebula: M27

Dumbbell Nebula: M27

Proper Motion and Parallax

Barnards Star – Click To See Motion

Data from StackImages.py

Date	t (years)	x (pixels)	y (pixels)
2012-06-21	-0.494	758.95	649.41
2013-06-06	0.461	758.24	665.87
2013-09-05	0.715	756.69	669.24
2014-04-10	1.307	758.11	679.03
2014-07-05	1.547	756.82	684.50
2014-10-27	1.844	756.31	690.32

$$x(t) = x_0 + v_x t + a \sin(2\pi t)$$

$$y(t) = y_0 + v_y t + b \cos(2\pi t)$$

- t is time in years
- Unknowns: x_0, v_x, a, y_0, v_y, and b
- 1 pixel = 0.575 arcseconds
- a = parallax
- $\sqrt{{v_x}^2 + {v_y}^2}$ = proper motion
- $\tan^{-1}(b/a)$ = orbital inclination

$$\text{distance} = 1/\text{parallax} = 1.90 \text{ parsec}$$

$$\text{proper motion} = 9.9 \text{ arcsec/yr}$$

Year: 5405

Resume Now

FOV: 90°

Max magnitude: 10.0

Show Constellation Lines Show Star Labels

Stars Moving Over Time

Use the sliders to change year & FOV. Click anywhere in the view to re-center.

Click here to see a stereoscopic 3D rendition.

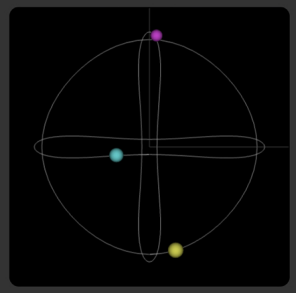
To change the view point, either type an Object Name (M, NGC, IC, or HD):
Barnards Star
or give a Direction to Look: Select
or enter RA and Dec coordinates
RA: 269.450, Dec: 4.693
or just click somewhere.

Note: Barnard's Star is being shown as magnitude 1 when in reality it is magnitude 9.5.

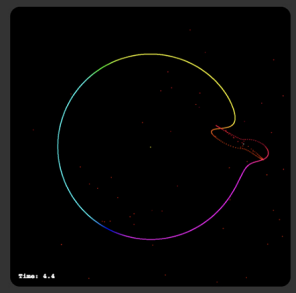
Star, Planet, Moon Dynamics

← Homepage

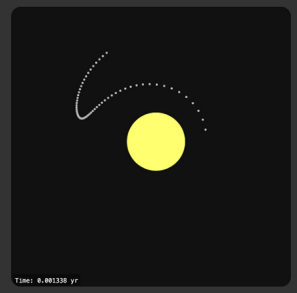
Click on the icons to see the dynamics



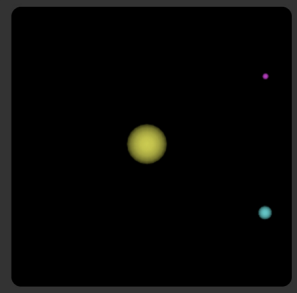
Ducati: Star/Planet/Moon



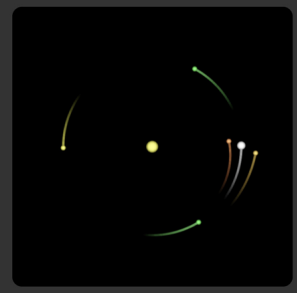
L4/L5 Accumulation of Star Dust



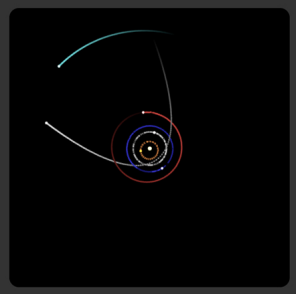
Saturn and Janus sized moons



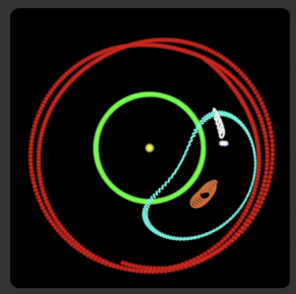
Lagrange 3-Body



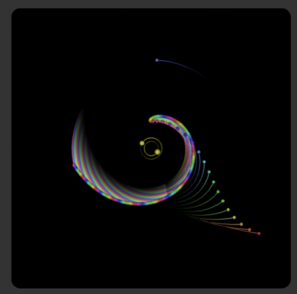
Lagrange L1 to L5



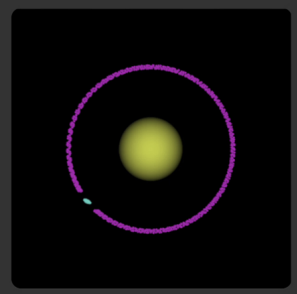
Solar System



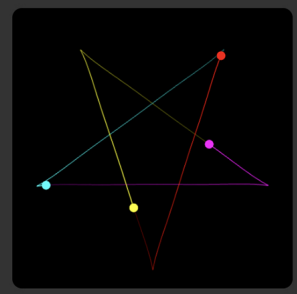
Earth Coorbital Asteroids



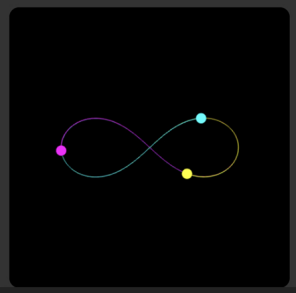
CircumBinary Planets

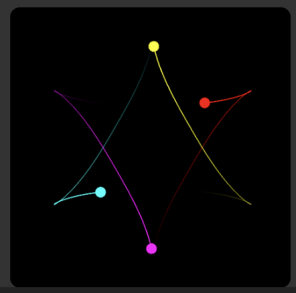


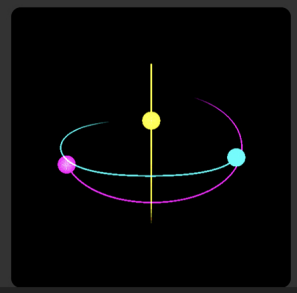
Horseshoe Orbit
Janus, Epimetheus and Saturn

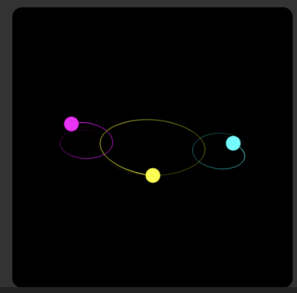


Ouyang-Xie Examples









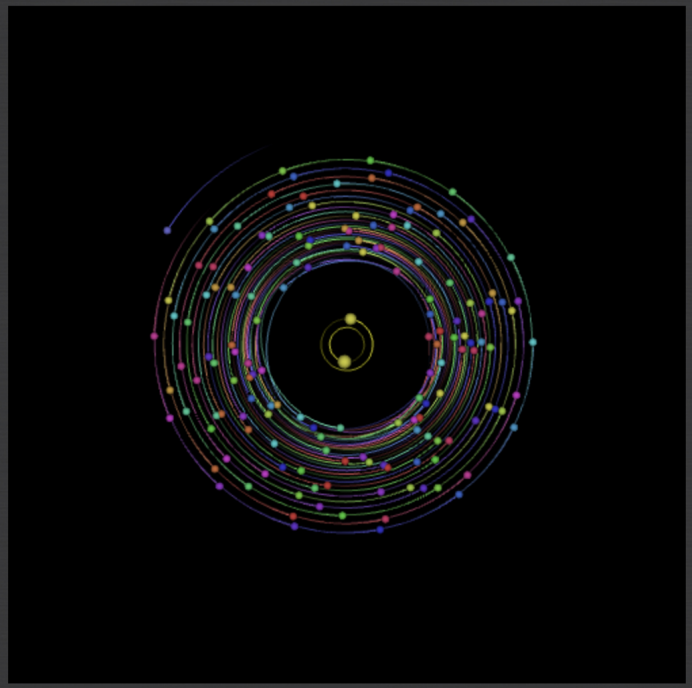
Circumbinary Planetary Systems

← All n-Body Animations

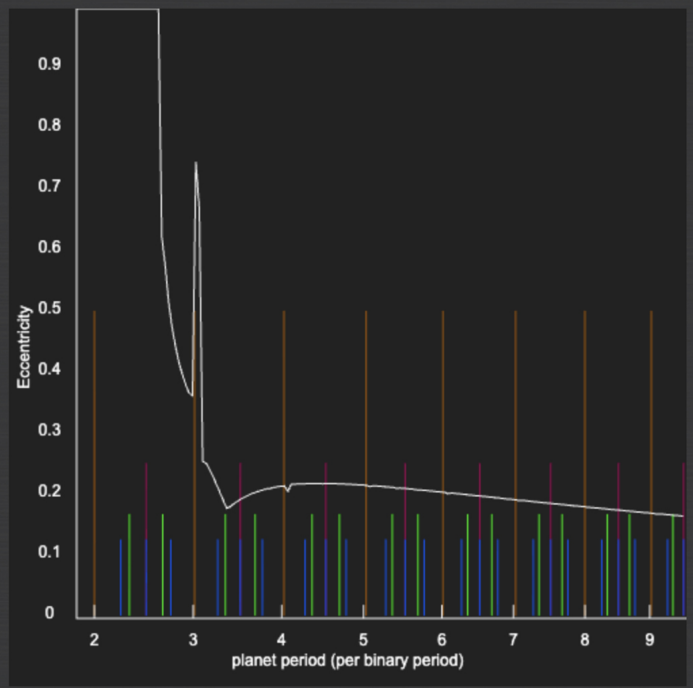
Shown here are 180 planets orbiting a binary star system. The yellow blobs in the center are the two stars. By default, their total mass is equal to the mass of our Sun. The smaller blobs are the 180 planets. They all have zero mass. Hence, they don't interact with each other. The one that is furthest out is a pale blue dot at 1au from the system's center of mass. Even though it has mass zero, we can think of it as representing Earth. The other planets are evenly spaced ranging from 0.3au to 0.9au. As you can see when the animation starts, the planets that are close to the center of mass have unstable orbits. You can speed up the animation by entering a larger number in the "Redraw dt" text box. Changing the value from its default of 1e-3 to 1.0 makes the whole thing go 1000 times faster.

The white plot on the right shows the eccetricities of each of the 180 orbiting planets. An eccentricity of 1 corresponds to a planet that has been ejected from this star/planet system. The colored vertical lines show orbital periods that are in resonance with the orbital period of the binary stars.

Time = 10.24



Eccentricity



Reset Pause/Run

Redraw dt: 1e-3. Integration dt: 1e-4.

Integration Method: Leapfrog. Trails: Show.

Stellar separation: 0.2 AU. Masses: Star 1 0.6 $M_\odot$ Star 2 0.4 $M_\odot$

Closest planet: 0.3 AU. Furthest planet (except Earth): 0.9 AU.

Binary star inclination: 0 degrees. Stellar velocity perturbation: 1.0

Drag mouse to rotate 3D model. Hold *shift* key to zoom in and out.

Building this webpage was inspired by many chats with Princeton student Sufia Birmingham '26.

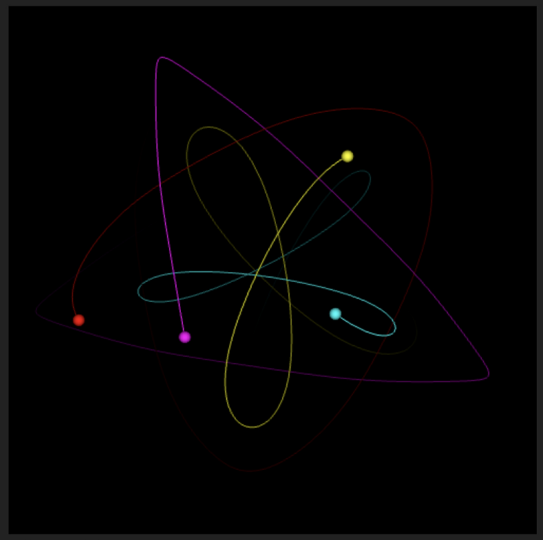
Periodic Planar Solutions to the n-Body Problem

← Homepage

Use the pull-down `Select an orbit' menu or click on the icons to check out other new orbits.

The first in the list is *Star of David*. I discovered it on June 24, 2013.

Click here to see in 3D a few hundred stable periodic orbits to the 3-body problem.



Time = 1.41

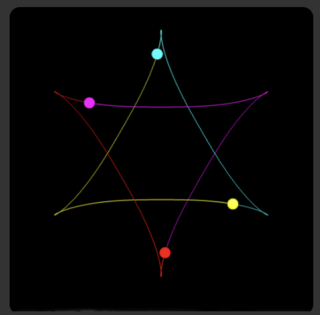
Reset | Pause/Run | Select an orbit: 5 Point Star (2.0,0.5,1.5,1.0)

Delay between frames: 30 ms. Redraw dt: 6e-2. Integration dt: 1e-4.

Integration Method: Leapfrog. | Toggle Counter-rotation | To check stability... | Perturb Orbits

Drag mouse to rotate 3D model. Hold *shift* key to zoom in and out.

The IAS15 integrator is a new high-precision integrator by Rein and Spiegel.



Star of David

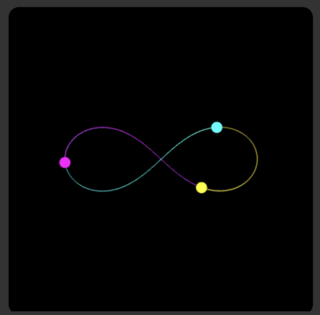


Figure Eight 3-Body

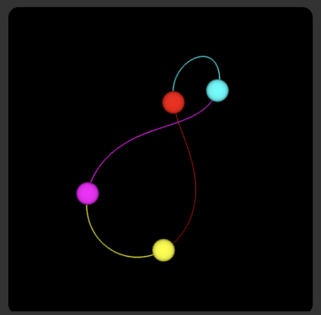
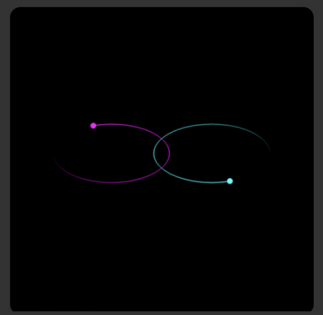


Figure Eight 4-Body



Double Ellipse

Periodic Solutions to the n-Body Problem
Discovered by XiaoMing Li and ShiJun Liao

Switch to 2D (single-eye) view

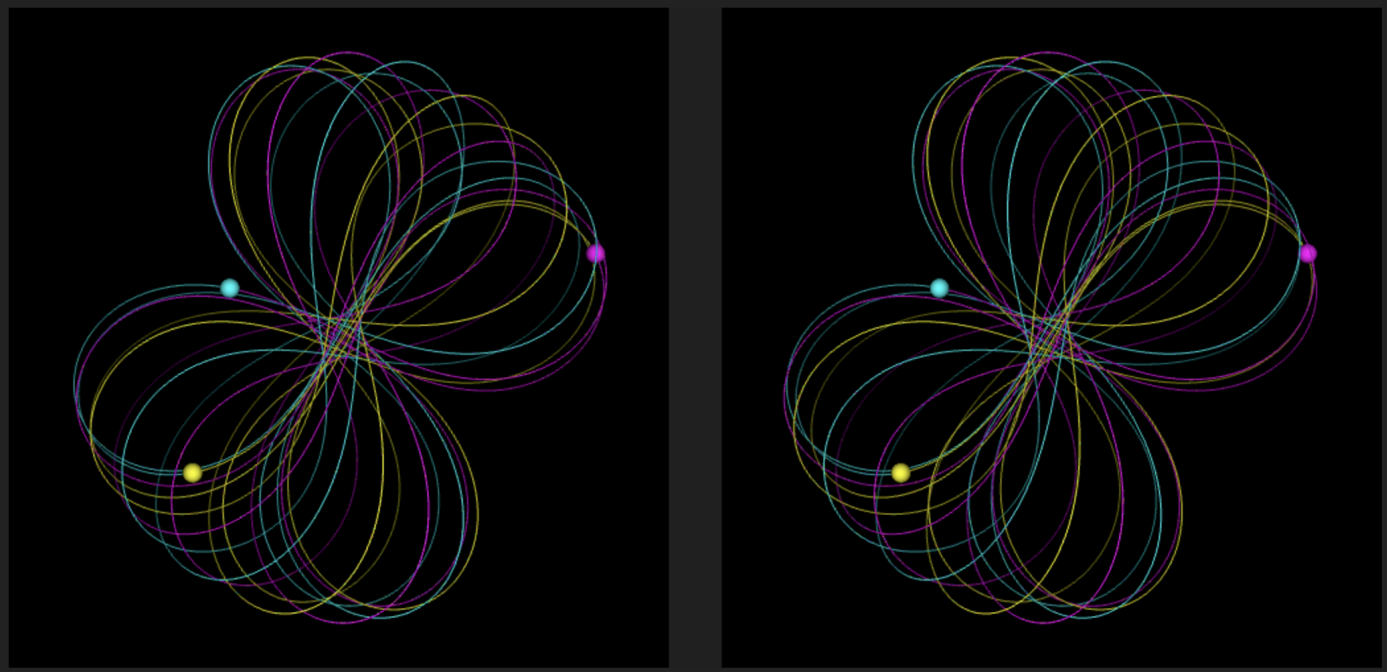
References: https://numericaltank.sjtu.edu.cn/three-body/2017-SCPMA-3body.pdf
https://arxiv.org/pdf/2508.08568

Point your left eye at the left image and your right eye at the right image and enjoy the 3D stereoscopic view.

Click and drag your mouse to change your viewing posiition.

Here are 185 equal-mass (mostly) stable periodic orbits: -- Select an orbit --

O 1497



Time = 0.50

Reset Pause/Run

Delay between frames: 30 ms. Redraw dt: 6e-2. Integration dt: 1e-4. Integration Method: IAS15.

Drag mouse to rotate 3D model. Hold *shift* key to zoom in and out.
The IAS15 integrator is a new high-precision integrator by Rein and Spiegel.

Supernovas

Crab Nebula: M1

Oct. 27, 2006

6500 yrs

Crab Nebula: M1

Mar. 26, 2019

6500 yrs

Crab Nebula – Analysis

First picture was taken Oct. 27, 2006.

Crab Nebula – Analysis

First picture was taken Oct. 27, 2006.

Second picture was taken Mar. 26, 2019.

Crab Nebula – Analysis

First picture was taken Oct. 27, 2006.

Second picture was taken Mar. 26, 2019.

The expansion factor is 1.288%. The time interval is 4533 days (12.41 years).

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If we denote the expansion factor by x and we assume a constant linear rate of expansion, then the formula for computing the date at which the supernova explosion took place is

$$\text{date} = 2006.8 - 12.41 * \frac{1}{x}$$

Crab Nebula – Analysis

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Putting $x = 0.01288$, we get

$$\text{date} = 1043$$

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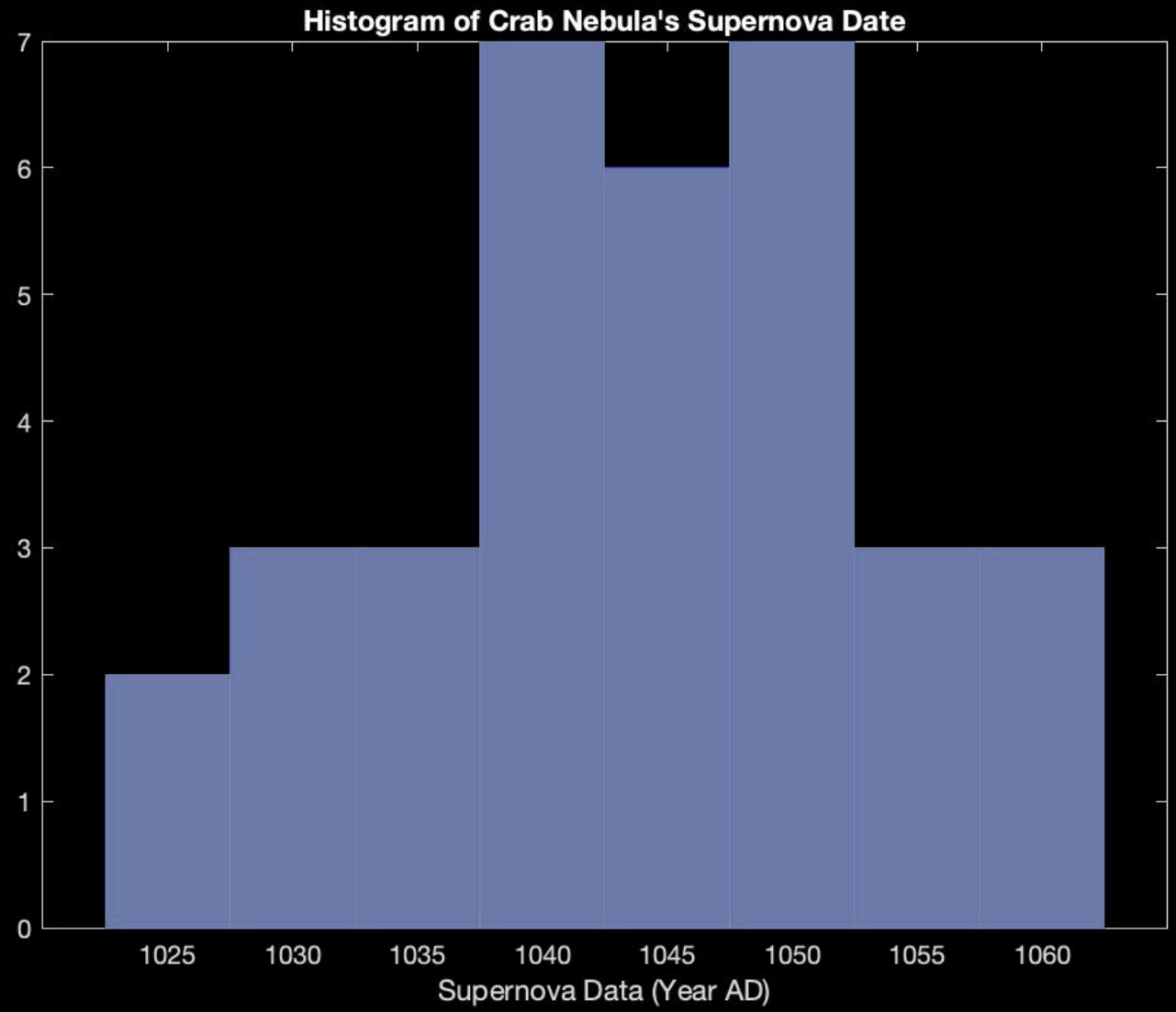
According to the historical record, the supernova took place in the year 1054.

I recomputed the estimate by subsampling the measurements 34 different ways. Here's the histogram showing the range of dates obtained:



The Whirlpool Galaxy: M51

May 9, 2005

The Whirlpool Galaxy: M51

July 10, 2005

The Whirlpool Galaxy: M51

June 7, 2011

The Pinwheel Galaxy: M101

May 25, 2023

The Pinwheel Galaxy: M101

May 25, 2023

No More Dynamics. Just Pictures.

Helix Nebula: NGC 7293

200 yrs

The Pleiades (Subaru): M45

444 yrs

Pacman Nebula: NGC 281

950 yrs

Horsehead Nebula: IC 434

1260 yrs

Orion Nebula: M42

1344 yrs

Running Man Nebula: NGC 1977

1500 yrs

Crystal Ball Nebula: NGC 1514

1520 yrs

Veil Nebula: NGC 6960 and 6992

2400 yrs

Western Veil: NGC 6960

2400 yrs

Eastern Veil: NGC 6992

Owl Nebula: M97

2400 yrs

Ring Nebula: M57

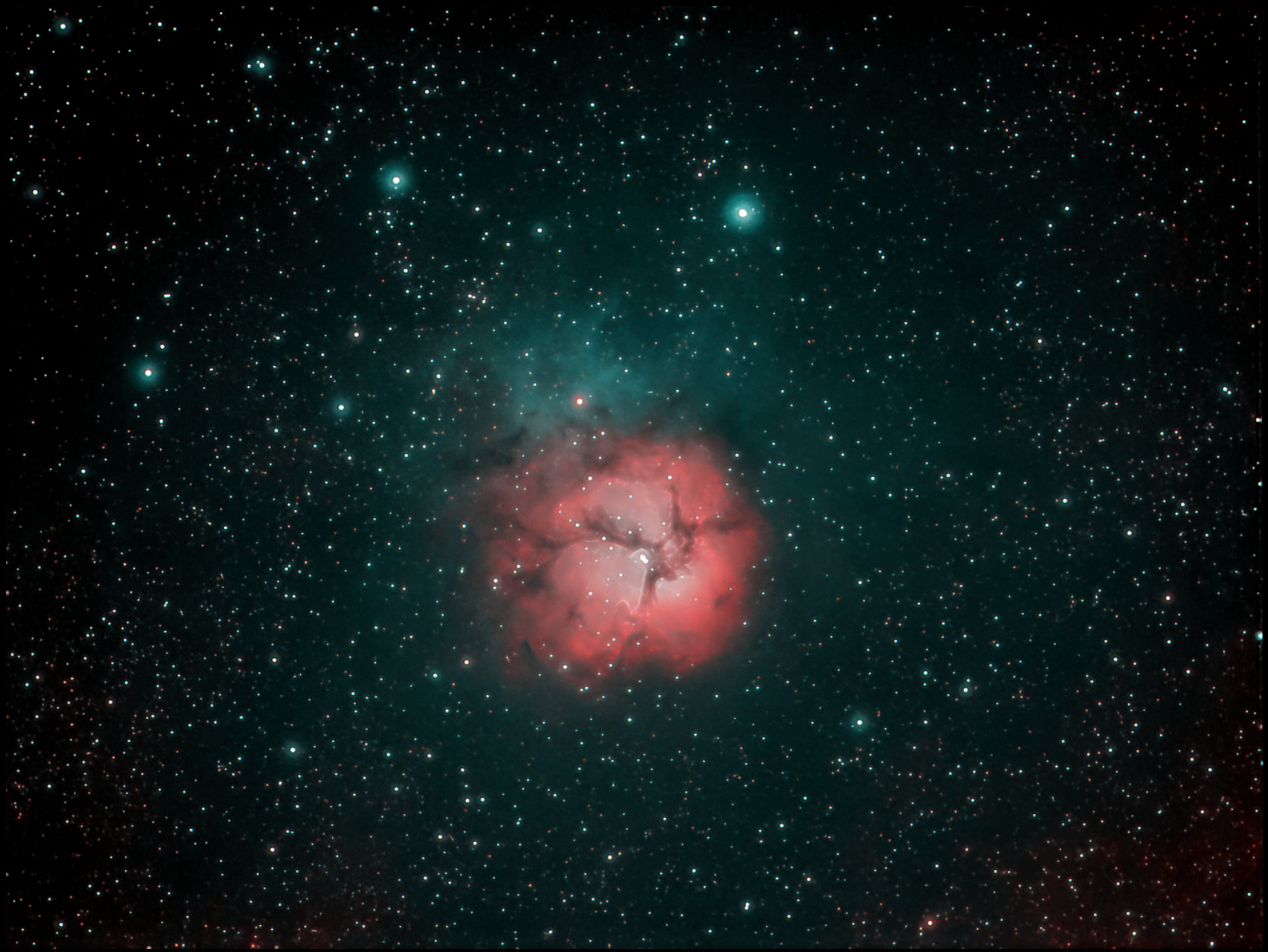
2567 yrs

The Lagoon Nebula: M8

4100 yrs

Trifid Nebula: M20

4100 yrs



Crescent Nebula: NGC 6888

5000 yrs

Jellyfish Nebula: IC 443

5000 yrs

Rosette Nebula: NGC 2237

5200 yrs

Eagle Nebula: M16

5700 yrs

NGC 6820

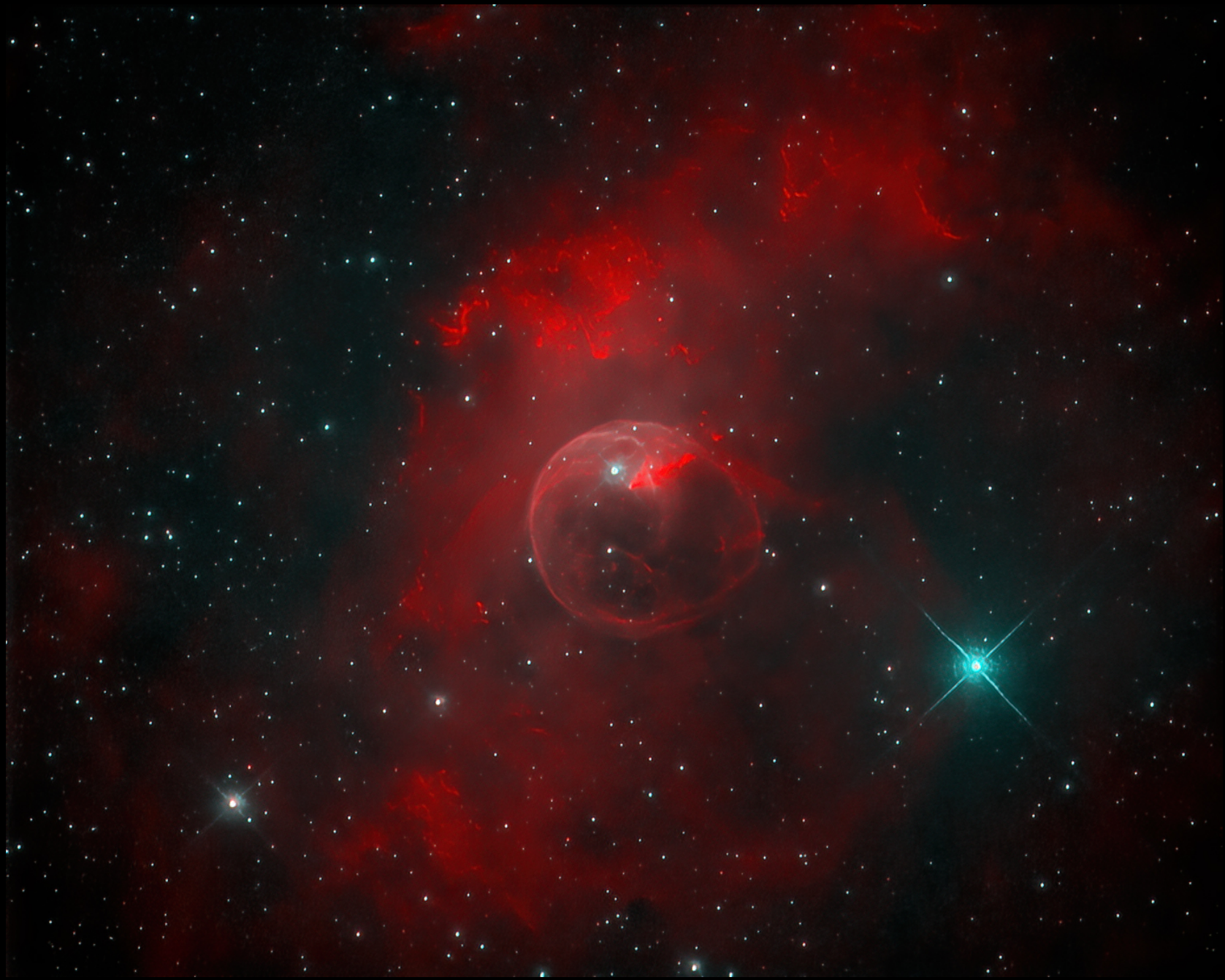
6000 yrs

Eskimo Nebula: NGC 2392

6520 yrs

Bubble Nebula: NGC 7635

9100 $\pm$ 2000 yrs



Globular Cluster: M13

22200 yrs

Looking Out Beyond Our Milky Way

The Andromeda Galaxy: M31

2450000 yrs

Sombrero Galaxy: M104

9600000 yrs

M81 and M82

11800000 yrs

Cigar Galaxy: M82

12000000 yrs

Galaxy Cluster: M106

24000000 yrs

The Leo Trio: M65, M66, NGC 3628

32000000 yrs

The Needle Galaxy: NGC 4565

42700000 yrs

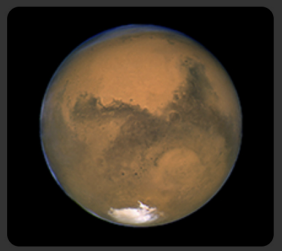
Welcome to the Universe in 3D



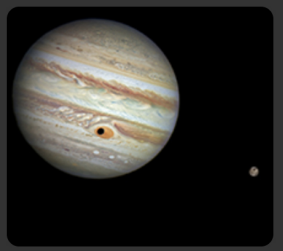



3D Pictures from the Book


Moon


Mars

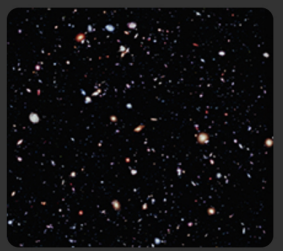

Comet Lovejoy


Jupiter and Ganymede


Mimas


Crab Nebula


Andromeda


Hubble Ultra Deep Field

Questions?