Imaging Detectors for Astronomy & Astrophysics

Quantum-Limited Imaging Detectors Workshop
Rochester Institute of Technology
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Teledyne
Providing the best images of the Universe
Domains of Astronomy & Earth Science

**Astronomy looks out**
Senses radiation coming in from the universe

**Earth Science looks in**
Senses radiation coming from the Earth

**Low Earth Orbit**
Astronomy & Earth Science

**Geosynchronous Orbit**
Primarily Earth observation

- Hubble Space Telescope (2.4-m) Low Earth Orbit
- ESO VLT 8.2-m telescope Ground-based (Chile)
Astronomy & Astrophysics – Vantage Points

- **Ground-based**
  - Nighttime
  - Daytime (solar astronomy)
- **Low Earth Orbit (LEO)**
  - Hubble Space Telescope (HST)
  - NASA Small Explorer missions
- **Lagrange Point 1**
  - Solar and Heliospheric Observatory (SOHO)
- **Lagrange Point 2**
  - Wilkinson Microwave Anisotropy Probe (WMAP)
  - James Webb Space Telescope (JWST)
  - Joint Dark Energy Mission (JDEM)
- **Planetary missions**

Lagrange Points of the Earth-Sun system (not drawn to scale!)
Constellation of Orion

What we see "flat" on sky

1,000 light years
A flight through the local universe
The Electromagnetic Spectrum
Atmospheric transmission
Not all of the light gets through atmosphere to ground-based telescopes
Spectral Bands
Defined by atmospheric transmission & detector material properties

Detector Zoology
The Eagle Nebula as seen with Hubble
The Eagle Nebula as seen in the infrared

M. J. McCaughrean and M. Andersen, 1994
Orion – In visible and infrared light

Orion – by IRAS
Our Sun

Far UV (28 nm)
### Energy of a photon

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Energy (eV)</th>
<th>Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>4.13</td>
<td>UV</td>
</tr>
<tr>
<td>0.5</td>
<td>2.48</td>
<td>Vis</td>
</tr>
<tr>
<td>0.7</td>
<td>1.77</td>
<td>Vis</td>
</tr>
<tr>
<td>1.0</td>
<td>1.24</td>
<td>NIR</td>
</tr>
<tr>
<td>2.5</td>
<td>0.50</td>
<td>SWIR</td>
</tr>
<tr>
<td>5.0</td>
<td>0.25</td>
<td>MWIR</td>
</tr>
<tr>
<td>10.0</td>
<td>0.12</td>
<td>LWIR</td>
</tr>
<tr>
<td>20.0</td>
<td>0.06</td>
<td>VLWIR</td>
</tr>
</tbody>
</table>

- Energy of photons is measured in electron-volts (eV)
- eV = energy that an electron gets when it “falls” through a 1 volt field.
JWST - James Webb Space Telescope
15 Teledyne 2K×2K infrared arrays on board (~63 million pixels)

- International collaboration
- 6.5 meter primary mirror and tennis court size sunshield
- 2013 launch on Ariane 5 rocket
- L2 orbit (1.5 million km from Earth)

JWST will find the “first light” objects after the Big Bang, and will study how galaxies, stars and planetary systems form.

- **NIRCam** (Near Infrared Camera)
  - Two 2x2 mosaics of SWIR 2Kx2K
  - Wide field imager
  - Studies morphology of objects and structure of the universe
  - European Space Agency / NASA

- **NIRSpec** (Near Infrared Spectrograph)
  - 1x2 mosaic of MWIR 2Kx2K
  - Spectrograph
  - Measures chemical composition, temperature and velocity
  - Canadian Space Agency
  - Three individual MWIR 2Kx2K
  - Canadian Space Agency

- **FGS** (Fine Guidance Sensors)
  - Acquisition and guiding
  - Images guide stars for telescope stabilization
  - Three individual MWIR 2Kx2K
  - Canadian Space Agency
An electron-volt (eV) is extremely small

1 eV  =  1.6 \cdot 10^{-19} \, J  \quad (J = \text{joule})

1 J  =  N \cdot m  =  \text{kg} \cdot m \cdot \text{sec}^{-2} \cdot m

1 \text{ kg raised 1 meter}  =  9.8 \, J  =  6.1 \cdot 10^{19} \, \text{eV}

- The energy of a photon is **VERY** small
  - The energy of a SWIR (2.5 \, \mu m) photon is 0.5 eV
- Drop a peanut M&M® candy from a height of 2 inches
  - Energy is equal to 6 \times 10^{15} \, \text{eV} \quad (\text{a peanut M&M® is } \sim 2\, \text{g})
  - This is equal to 1.2 \times 10^{16} \, \text{SWIR photons}
    - 1 \text{ million } \times 1 \text{ million } \times 12,000
    - The number of photons that will be detected in ~1 million images from the James Webb Space Telescope (JWST)
    - A 2-inch peanut M&M® drop is more energy than will be detected during the entire 5-10 year lifetime of the JWST!
The Ideal Imaging Detector

- Detect 100% of the photons
- Each photon detected as a delta function
- As many pixels as desired
- Time tag for each photon
- Measure photon wavelength
- Measure photon polarization
Instrument goal is to measure a 3-D data cube

But detectors are 2-dimensional!
- Detectors are **BLACK & WHITE**
- Can not measure color
- Only measure intensity

Optics of the instrument are used to map a portion of the 3-D data cube onto the 2-D detector
The Ideal Imaging Detector

- Detect 100% of photons
- Each photon detected as a delta function
- Large number of pixels
- Time tag for each photon
- Measure photon wavelength
- Measure photon polarization

- ✓ Up to 98% quantum efficiency
- ✓ One electron for each photon
- ✓ ~1,400 million pixels (>10^9)
- ❌ Not for framing detectors
- ❌ No – defined by filter
- ❌ No – defined by filter

Plus READOUT NOISE and other “features”

But we can still be quantum-limited in many cases!
Photon Noise Limited Imaging

- An ideal imaging system should be limited only by the Poisson statistics of light detection and the imagination of the user.

- Poisson statistics
  - Variance of signal equals the mean of the signal
  - For mean > 10, Poisson statistics is very similar to Gaussian statistics
Signal-to-Noise Ratio

Ideally, for an imaging system:

$$\text{SNR} = \frac{N_{\text{ph}}}{\sqrt{N_{\text{ph}}}} = \sqrt{N_{\text{ph}}}$$

But we have less than 100% quantum efficiency (QE) and other noise sources:

- Background photons, $N_b$
- Dark current, $N_d$
- Readout noise, $\sigma_{\text{RN}}$

$$\text{SNR} = \frac{N_{\text{ph}} \cdot \text{QE}}{\sqrt{N_{\text{ph}} \cdot \text{QE} + N_b \cdot \text{QE} + N_d + \sigma_{\text{RN}}^2}}$$
Noise Sources

• Background Light
  – Thermal radiation
  – OH airglow
  – Zodiacal Light

• Dark Current
Thermal Radiation

Ultraviolet

Infrared
OH airglow (1.0-1.9 μm)

- OH provides a constant source of illumination in the near infrared
- OH created by the reaction: \( \text{H} + \text{O}_3 \rightarrow \text{OH} + \text{O}_2 \)
- Thin emitting layer at ~85 km altitude
- Daytime intensity is 3x nighttime intensity, and intensity drops 40% during the night
OH airglow (1.0-1.9 μm)
Zodiacal Light – the ultimate limit to faint astronomy
In silicon, dark current usually dominated by surface defects.

\[ f(v) = 4\pi \left( \frac{m}{2\pi kT} \right)^{3/2} v^2 \exp \left[ \frac{-m\nu^2}{2kT} \right] \]

These vibrations have enough energy to pop electron out of the valence band of the crystal lattice.
Imaging Detector Parameters

- Wavelength
  - Material
  - Quantum efficiency
- Flux
- Pixel pitch
- Number of pixels
- Frame rate
- Size, weight, power
  - Operating temperature
- Shutter
  - Snapshot (integrate then read, integrate while read)
  - Rolling shutter
  - Duty cycle
- Crosstalk
  - Diffusion
  - Electrical

- Dynamic range
  - Number of bits
- Charge transfer efficiency
  - for CCDs
- Interface
  - Analog control, or digital input
  - Analog output, or ADCs on chip
  - Number of readout ports
- Multiple integration sites per pixel
- Processing on the detector
  - Event driven readout
- Environmental requirements
  - Radiation
  - Vibration
- Storage time / operation lifetime

Detectors are a series of trade-offs
Can not optimize all parameters at the same time
Application Areas

• **Measuring the effects of dark energy and dark matter**
  – Expansion history of the universe
  – Detector Challenge: Very long integrations, with very low noise

• **Ground-based adaptive optics**
  – Overcoming the blurring of the Earth’s atmosphere
  – Detector Challenge: High speed, low noise readout

• **Jupiter-Europa mission**
  – Exploring the liquid water world that may be hospitable to life
  – Detector Challenge: High radiation environment
Cosmic Epochs

- 13.7 billion years: Present
- Galaxy A1689-zD1: ~700 million years after the Big Bang
- ~300,000 years: “Dark Ages” begin
- ~400 million years: Stars and nascent galaxies form
- ~1 billion years: Dark ages end
- ~4.5 billion years: Sun, Earth, and solar system have formed

Today

- Dark Energy 72%
- Dark Matter 23%
- Atoms 4.6%
Raisin cake model of expanding Universe
Relative Size of the Universe

\[ \Omega_M = 0 \]

- \( \Omega_M < 1 \) Open
- \( \Omega_M = 1 \)
- \( \Omega_M > 1 \) Closed

Time (billions of years)

- 14
- 9
- 7
Today
White Dwarfs
Progenitors of Type Ia Supernovae

White Dwarf
will explode when it grows to 1.4 solar masses
Relative Size of the Universe

Time (billions of years)

- Fainter
- Larger Redshift

Open $\Omega_M < 1$
Closed $\Omega_M > 1$
Flat $\Omega_M = 0$

$\Omega_M$ represents the density parameter of the universe. Values greater than 1 indicate a closed universe, less than 1 an open universe, and exactly 1 a flat universe.
Relative Size of the Universe

\[ \Omega_M = \frac{\text{matter density}}{\text{critical density}} \]

- \( \Omega_M > 1 \) Closed Universe
- \( \Omega_M < 1 \) Open Universe
- \( \Omega_M = 1 \) Flat Universe

Fainter

Larger Redshift

Time (billions of years)

- 14
- 9
- 7
Today
Baryonic Acoustic Oscillations (BAOs)


Was in the local universe (z<0.5, 0.5 Gpc$^3$), with only 47,000 galaxies but it showed the technique works.
Gravitational Lensing

Evidence of Gravity due to dark matter
Dark Energy Mission Detector Requirements

• Measure universe with three methods:
  – Supernovae
  – Baryonic acoustic oscillations
  – Gravitational Lensing

• Detector Requirements
  – High quantum efficiency (>80%)
  – Very low noise
    • Negligible dark current
    • Total noise (readout + dark current) less than zodiacal light
    • Total noise < 7 e-
  – Low power
  – High spatial resolution for gravitational lensing
    • Small pixels for visible light detection
  – Quantum-limited imaging detectors would be ideal
Atmospheric Distortions
Adaptive Optics Animation
Imaging the galactic center

The Galactic Center at 2.2 microns

Adaptive Optics OFF
Simplified AO system diagram
Adaptive Optics Wavefront Sensor Detector

• Requirements
  – High quantum efficiency (>80%)
  – High frame rate: up to 1000 Hz
  – Very low noise
    • Negligible dark current
    • Readout noise less than 5 electrons for infrared
    • Readout noise less than 2 electrons for visible
  – At least 4×4 pixels per subaperture
  – Up to 20×20 pixels per subaperture for elongated laser guide star
    • For the Extremely Large Telescopes (24-m, 30-m, 42-m)
      – 2000×2000 pixels
      – 1000 Hz frame rate
      – < 3 e- noise (~1 e- noise preferred)
  – Quantum-limited imaging detectors would be ideal
Image of Jupiter taken by Adaptive Optics
Jupiter’s Galilean Moons

Io

Europa

Ganymede

Callisto
Jupiter’s Moon
Europa
Jupiter’s Magnetosphere
Jupiter’s Magnetosphere

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Earth</th>
<th>Jupiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial radius (km)</td>
<td>6.38x10^3</td>
<td>7.14x10^4</td>
</tr>
<tr>
<td>Magnetic moment (G·cm^3)</td>
<td>8.1x10^{25}</td>
<td>1.59x10^{30}</td>
</tr>
<tr>
<td>Rotation period (hr)</td>
<td>24.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Aphelion/perihelion (AU)</td>
<td>1.01/0.98</td>
<td>5.45/4.95</td>
</tr>
</tbody>
</table>

- Jupiter is roughly 10 times the size of the Earth while its magnetic moment is 2x10^4 larger.
- As the magnetic field at the equator is proportional to the magnetic moment divided by the cube of the radial distance, the Jovian magnetic field is proportionally 20 times larger than the Earth’s.

- The energy and flux levels of trapped particles in the Jovian system can be much higher than those at the Earth or in the interplanetary space.
Possible Jupiter / Europa Mission Timeline

- Launch 2020
- End of Prime Mission

Jovian Tour:
- Io Encounters
- Europa Encounters
- Ganymede Encounters
- Callisto Encounters

Europa Science:
- Total Ionizing Dose (TID)
- Radiation Design Point

Radiation Dose (Mrads) Or Data Volume (Tbits)

Data Volume:
- Total Ionizing Dose (TID)
- 2.7x10^8 Rads (Si)
- 1.5x10^8 Rads (Si) (at EOI)
- Cassini Prime Mission: 2.8 Tb
- Galileo: 0.25 Tb
Jupiter-Europa Mission

• Special detector requirements
  – Tolerance to high levels of radiation (Mrad level)
  – Planetary protection
    • Ability to “bake out” the detector to kill germs, so no contamination of Europa when orbiter hits surface at end of the mission