A Generic Example:
Exploration of Observable Parameter Space

- A purely general approach to a systematic exploration of the universe
- Every astrophysical observation (or even a survey) carves out a specific slice in the parameter space, and is thereby limited
- Usually, new discoveries are made when some new portion of the observable parameter space opens up (e.g., a new wavelength range - but it could be improved resolution, etc.)
- Once sources are identified and catalogued in some survey or a federation thereof, they form data vectors in a highly multidimensional parameter space:
  - Sources of different types (e.g., stars, galaxies, quasars…) form clusters and correlations in this parameter space
  - Outliers may represent rare, unusual, or even new types of objects

Covering the Observable Parameter Space

(examples from M. Harwit)

The Observable Parameter Space

Non-Electromagnetic Observations (CR, GW, …)

Depth
Area Coverage
Wavelength Coverage

Spectroscopic Resolution, Polarimetry
Angular Resolution
Precision and Dynamical Range

The Time Domain:
Depth, sampling, baselines, …
A Parameter Space Example: “Icebergs in the Sky”
Exploring the Low Surface Brightness Universe

With Arecibo H I Observations

$\nu = 5500 \text{ km/s}$

$\nu = 2500 \text{ km/s}$

Background Enhancement Technique demonstrated on two known M31 dwarf spheroidals

(Brunner et al.)
**Exploring the Low Surface Brightness (Low Contrast) Universe**

Comparison between HI, Hα, and 100µ Diffuse Emission

DPOSS red image

IRAS 100 Micron Image

Brunner et al.

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**Time Domain Astrophysics**

- **Moving objects:** Solar system, Galactic structure, exoplanets
- **Variability**
  - Modulation along the LOS: microlensing, ISS, eclipses, variable extinction ...

**Physical causes of intrinsic variability:**
- Evolution (structural changes etc.), generally long time scales
- Internal processes, e.g., turbulence inside stars
- Accretion / collapse, protostars to CVs to GRBs to QSOs
- Thermonuclear explosions
- Magnetic field reconnections, e.g., stellar flares
- Line of sight changes (rotation, jet wiggles…)

Variability is known on time scales from ms to 10^{10} yr

Synoptic, panoramic surveys ➔ event discovery

Rapid follow-up and multi-λ ➔ keys to understanding

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**Things That Move in Our Solar System**

- Dwarf planets and KBOs
  - Sedna, Xena, …
  - NEAT, Catalina, etc.

- Killer Asteroids
  - Tunguska

M. Brown et al.

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**Donald Rumsfeld’s Epistemology**

*There are known knowns, There are known unknowns, and There are unknown unknowns*
**Intrinsically Variable Phenomena**

- Things we know about:
  - **Stars:** oscillations, noise, activity cycles, atmospheric phenomena (flares, etc.), eclipses, explosions (SNe, GRBs), accretion (CVs, novae), spinning beams (pulsars, SS 433, …)
  - **AGN:** accretion power spectrum, beaming phenomena
- Things we see, but don’t really understand:
  - Faint fast transients
  - Archival optical transients (OT)
  - Megaflares on normal stars
- Things we expect to see, and maybe we do:
  - Breakout shocks of Type II SNe
  - SMBH loss cone accretion events
  - BH mergers (LIGO, LISA?), QSO formation…?
- Things as yet unknown and/or unexpected:
  - Manifestations of ETCs? (SETF?)

**DPOSS Pilot Search for Highly Variable Objects**
(Using plate overlaps)

**Spectroscopic IDs:**
- 35% QSOs (1/2 radio loud)
- 18% CVs
- 18% M dwarfs
- 6% Earlier type stars
- 23% Unidentified (likely BL Lacs?)

**Scans 3 hours apart (note the absence of low-z QSOs):**

**Δt ~ 2 years. QSOs dominate the variable sample!**
**Quasar Variability**

Typically quantified using the structure function,

\[
S(\tau) = \left\{ \frac{1}{N(\tau)} \sum_{i<j} |m(i) - m(j)|^2 \right\}^{1/2}
\]

where \( \tau = t_j - t_i \)

Structure function for QSO variability (SDSS and POSS measurements)

- \( SF_0 = 0.32 \times (1 - \exp[-(\Delta t/390 \text{ d})^{0.55}]) \)
- \( SF_0 \propto \Delta t^{0.35} \)

**How Quasars Were Not Discovered**

Noted as variable sources even in the 19th century, but … misclassified as variable stars

Historical (archival) lightcurve of 3C273, starting from the 1880’s …

**Beamed AGN: Blazars (Cosmic Accelerators)**

Presumed sources of TeV γ-rays and possibly some UHECRs

Important for the GLAST mission, and ground-based TeV and UHECR experiments (e.g. Auger)

**PQ Variability of AGN and Blazars**

- Characterize the high-ampl. variability of known QSOs and especially Blazars
- Use to devise a pure optical variability (and color?) selection of Blazars
- Are we missing a population not found by the traditional radio or X-ray selection?
- A good multi-λ synergy with GLAST, TeV γ-ray, and UHECR surveys and experiments
Accretion Flares From Otherwise Quiescent SMBHs
Tidal disruption of passing-by stars, and fallback. Expected rate \( \sim 10^{-4}/\text{galaxy/yr} \), \( L_{\text{peak}} \sim 10^{44} \text{erg/s} \)

Komossa et al. (Rosat) 5 candidate events in X-rays

Gezari et al. (GALEX) A few candidate events in UV

Megaflares From Normal (?) Stars
An example from DPOSS: A normal, main-sequence star which underwent an outburst by a factor of \( >300 \).

There is some anecdotal evidence for such megaflares in normal stars (Schaefer).

The cause(s), duration, and frequency of these outbursts is currently unknown.

Flaring M Dwarfs (a vermin of the synoptic sky surveys?)
Lynx OT (Catalina Sky Survey)

(just like the Solar flares, but much, much bigger)

PALS-1: A possible gravitationally magnified U-band dropout (\( z \sim 3.3? \)) behind Abell 267 (Stern et al.)

Variable sources in the centers of apparently normal galaxies at \( z \sim \) few tenths

(Totani et al., SUBARU)
**PQ Search for Low-z Supernovae**

In collaboration with R. Ellis, S.R. Kulkarni, A. Gal-Yam, and the LBL SN Factory

- Calibration of the SN Ia Hubble diagram
- New standard candles from SN II
- Endpoints of massive star evolution

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**Discoveries of Peculiar Supernovae**

OT 060520:143933+054636, SNF discovery, Caltech follow-up
Peculiar SN Ib, similar to 1984L?

A. Mahabal et al., ATEL 827

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**Faint, Fast Transients From DLS**

(Tyson, Becker, et al.)

Some are flaring M-stars, some are extragalactic, …

→ A heterogeneous population!

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**Optical Transients in DPOSS**

A possible orphan afterglow discovered serendipitously in DPOSS: an 18th mag transient associated with a 24.5 mag galaxy. At $z_{est} \sim 1$, the observed brightness is $\sim 100$ times that of a SN at the peak.

**How many do we expect to see?**
Depending on the beaming factors, there should be $\sim 10$ afterglows down to $R \sim 20$ mag per all-sky snapshot.

… But it could be something else entirely…
Examples of DPOSS Transients

Unidentified Archival Transients in PQ

The Palomar-Quest Event Factory

Real-Time Discovery of Transients

Examples of optical transients discovered in the real time in Sept.’06, using a prototype real-time pipeline
The Emerging Global VOEvent Network
(from Seaman & Warner 2006)

The VOEventNet Project
PI: R. Williams
- A telescope sensor network with a feedback
- Scientific measurements spawning other measurements and data analysis in the real time
- Please see http://voeventnet.org

An Unidentified PQ Real-Time Event
PQOT 070519:143933+054636 A. Drake et al., ATel 1083
Discovery images:

Baseline comparison:
- Initially very blue, but getting redder rapidly
- Slow fading, 0.3 - 0.4 mag/day, reached plateau
- Possible SN ?
- Followed up by SWIFT (ATel 1088) - no X-ray detection
Asteroids: A Major Contaminant!

- We have many “transient” detections, but they are mostly asteroids
- We find \(~ 1 - 3\) asteroids / deg\(^2\) down to \(~ 20 - 21\) mag, per epoch

Mitigation:
- Optimized cadence: scan and rescan the same night \(~ 3 - 4\)h apart
- Crossmatch to asteroid DB’s (Horizons, IMCCE)
- Improved proper motions and colors

Towards Automated Event Classification

A necessity for large synoptic surveys

Event parameters: \(m_1(t), m_2(t), \ldots\)
\(\alpha, \beta, \mu, \ldots\)
image shape...

Event Classification Engine

Expert and ML generated priors

Classification probabilities (evolving, iterated)
Some Things We Have Learned
(from DPOSS, SDSS, DLS, PQ …)
• In a single-pass snapshot survey there are ~ $10^{-2}$ astrophysical transients/deg$^2$ down to ~ 21 mag at high Galactic latitudes
• Most of the transients and variables are known types of objects; stars dominate on short time scales (~ minutes to months), AGN on longer time scales (~ years and beyond)
• Populations of as yet unidentified transients do exist; some may be new types of objects or phenomena
  – Real-time follow-up is necessary in order to understand them
• The quality of the baseline/fiducial sky is a key issue
  – It must be deep, clean, complete, and wavelength-matched
  – Generating a standard, dynamically evolving, annotated, multi-$\lambda$, baseline sky may be a good community (VO) project; we are developing a prototype from PQ

This is a Rapidly Evolving Field!
• Now: data streams of ~ 0.1 TB / night, ~ 10 - $10^2$ transients / night (SDSS, PQ, various SN surveys, asteroid surveys)
• Forthcoming on a time scale ~ 1 - 5 years:
  ~ 1 TB / night, ~ $10^4$ transients / night
  (PanSTARRS, Skymapper, VISTA, VST …)
• Forthcoming in ~ 5 - 10 years: LSST, ~ 30 TB / night, ~ $10^5$ - $10^6$ transients / night

Time-Domain Astronomy is the VO “Killer App”
Synoptic, panoramic surveys $\rightarrow$ Event discovery
Rapid follow-up and multi-$\lambda$. $\rightarrow$ Keys to understanding
Massive data streams + rapid, automated response
$\rightarrow$ No humans in the loop (need machine intelligence)

Some Thoughts on Time Domain Astronomy
• Scientific motivation and opportunities
  – A very rich variety of astrophysical phenomena: from asteroids to cosmology, extrasolar planets to extreme relativistic physics
  – Time domain can provide unique new insights
  – Time domain astronomy ≠ small (telescope) science
    Rather, it is intrinsically optimal for telescope systems
• Distinguish general surveys vs. dedicated experiments
  – The same synoptic survey data streams can (and do) serve multiple scientific goals
  – The same infrastructure can serve multiple follow-up needs
• Event discovery is just a start: 99% of the astrophysics is in the follow-up, and mostly in optical spectroscopy
  – Spectroscopic follow-up will be a key bottleneck for any synoptic sky survey!

What Are the Implied Technological and Methodological Needs?
• Data discovery and access mechanisms
• Data federation in both catalog and image domains
• Manipulation tools for combined data sets
• On-demand source re-extraction from panoramic imagery
• Clustering analysis tools in the catalog domain
• Visualization, visualization, visualization!
• Statistical analysis tools
• Methods to compare data and numerical simulations
• Automated robotic telescope and software systems for time domain exploration, event publishing mechanisms
  … etc., etc.