Time-Domain Science with ULTIMATE-Subaru

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Time-domain science

- Transients
  - supernova, gamma-ray bursts, GW sources, ...
- Variable stars

Subaru/HSC (Tominaga, Morokuma, MT+ 2015)
3 parameters for time-domain survey

- Cadence & # of visits (time resolution)
- Wider FOV & better sensitivity (no demand for NBF)
- Most of transient surveys have been done in optical/BBF
Why transient surveys in NIR?

- Nearby supernovae (reddened)
- High-redshift supernovae (redshifted)
- Gravitational wave sources (intrinsically red)
Missing supernovae?

star formation rate => supernova rate

\[ R_{SN}(z) = \dot{\rho}_*(z) \int_{M_{min}}^{M_{max}} \frac{\psi(M) \, dM}{\int_{0.1}^{100} M \, \psi(M) \, dM} \]

Summary of Cosmic SNR Measurements

- The Supernova Legacy Survey (SNLS) has published the most precise SNR measurement at

The scope of the rate measurements depend on a combination of limiting magnitude, SN luminosity function, and dust correction (see the discussion).

The numbers of CC SNe detected are too low by a factor of approximately 2 (Horiuchi et al. 2011).

Indeed, the measurements of Dahlen et al. (2004) and Mattila et al. (2012) have a trend—much better than their uncertainties would suggest. However, since the measurements of Dahlen et al. (2004) are well fit by a smoothed broken power law of the form (Y \cdot \psi(M) \, dM)/(\int_{0.1}^{100} M \, \psi(M) \, dM), it is in good agreement with a range of recent SFR measurements.

The calibration factors derived from stellar population synthesis are then smaller than the normalization discrepancy, and the significance of the discrepancy is at the 3.2 \sigma level (Hanish et al. 2010). The Lick tables for the local SFR at 0.8–1.0 Mpc of Mattila et al. (2012) is approximately 0.8–1.0 Mpc.

The most reliable SNR measurement is that by LOSS (Dahlen et al. 2004), which uses excellent deep, wide-field NIR data in four independent sightlines. We also include the data point. The scope of the rate measurements depend on a combination of limiting magnitude, SN luminosity function, and dust correction (see the discussion).

In Section 2, we systematically examine the rate measurements depend on a combination of limiting magnitude, SN luminosity function, and dust correction (see the discussion).

We adopt the dust-corrected SFR compilation of Hopkins & Beacom (2006) as the magnitude at which the detection efficiency is 50%.

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Fundamental questions in stellar astrophysics

Minimum mass of supernova?
8 Msun? 10 Msun?

Do all massive stars explode?
Not necessarily

Population and mass function of BHs (=> GWs)
Observational uncertainty: dust extinction

Optical surveys miss \(\sim\) 20\% of SNe??  

Demand for transient survey in NIR

Too small FOV \(\Rightarrow\) only LIRG and ULIRG (w/ AO)

LIRG IRAS 18293-3413  
VLT/NACO (K-band)

Arp 299 (\(\sim\)2 SN / yr expected!)  
HST/NICMOS (F164N)

Mattila+12
ULTIMATE: Wide-field non-targeted transient survey

- “K-only” survey (survey design C)
  - 20 deg² over 5 yr, 5 hr (300 min) / FOV, 26.2 mag depth
    => ~23.5 mag x 100 epochs (3 min each)
  - Required time sampling ~ 5 day
    => 100 epochs over ~2 yr baseline
- ~ 80 supernovae! (< 500 Mpc)
  - The first systematic SN rate measurement in NIR

Pros: Good use of wide-field capability
Cons: WFIRST (0.3 deg²) can do better
  (wider surveys with better sampling/control)
* JH & K are not so different in terms of extinction
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Supernova as tracers of high-z Universe

“Superluminous” SN: \( L \sim 10^{8-10} \, \text{L}_{\odot} \)

Smartt 2012
Superluminous SNe are detectable @ z ~ 7
SN rate => # of massive stars
UV or dust emission => Star formation rate

GRB rate => SFR
Robertson & Ellis 2012

Caveats:
Metallicity
dependence of
SN (GRB) progenitor
ULTIMATE: Deep IR transient survey?

- “K-only” survey (C)
  - 20 deg$^2$ over 5 yr, 26.2 mag depth
  - ⇒ ~25 mag x 10 epochs over 3 yr
- ~ 10 SNe @ z>6
  - small number, but still among best in 2020s

Pros: K is slightly better than JH (Euclid/WFIRST) for z>7
Cons: WFIRST can go deeper

Coordinated survey with HSC/LSST + WFIRST?
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Dawn of GW astronomy

GW 150914
BH-BH merger (~30 Msun) @ 400 Mpc

NEXT!
NS-NS merger (~< 200 Mpc) or BH-NS merger (~< 800 Mpc)

N ~30 (0.3-300) events/ 1 yr

LIGO Scientific Collaboration and Virgo Collaboration, 2016, PRL, 061102
The 2nd is also BH-BH merger (released on this Wed)

R. Flaminio’s talk yesterday

GW 151226
BH-BH merger
(~14+8 Msun) @ 440 Mpc
~ 100 galaxies / 1 deg$^2$ (< 200 Mpc)

SDSS
Localization
~ 600 deg$^2$ (GW150914)
~ 1400 deg$^2$ (GW151226)
(\(< 10 \text{ deg}^2 \text{ with Advanced Virgo and KAGRA})

Detection of electromagnetic (EM) counterparts is essential
- Redshift (distance)
- Host galaxy
- Local environment


- No plausible EM counterpart was detected for GW150914
  (neither for GW151226 so far)
- EM emission from BH-BH merger??
Electromagnetic signature from **NS** mergers (powered by radioactive r-process nuclei)

![Graph showing magnitude vs. time for optical (i) light.](image)

**Optical (i)**

- **Time (days)**
  - **Magnitude (AB)**
  - **200 Mpc**
  - **10^{-2} Msun**
  - **8m-class (~10 min)**
  - **10^{-3} Msun**

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**MT & Hotokezaka 13, MT+14, MT 16**

Subaru/HSC for GW151226 (50 deg^2) (J-GEM, Yoshida et al. 2016, GCN 18840)

**Brightness of the emission => Ejected mass of r-process elements**
**NS merger as a possible origin of r-process elements**

**Event rate**

\[ R_{NSM} \sim 100 \text{ event/Myr/Galaxy} = 10^{-4} \text{ event/yr/Galaxy} \]

**NS-NS merger rate**

Within 200 Mpc

\[ \sim 30 \text{ GW events/yr} \] (~0.3-300)

**Ejection per event**

\[ M_{ej}(r\text{-process}) \sim 10^{-2} \text{ Msun} \]

\[ M(\text{Galaxy, r-process}) \sim M_{ej}(r) \times (R_{NSM} \times t_G) \]

\[ \sim 10^{-2} \times 10^{-4} \times 10^{10} \sim 10^4 \text{ Msun} \]
Importance of NIR: brighter/longer timescale

- $L_{bol} \sim L_{IR}$ => Mass of ejected material
- Smoking gun: red and featureless spectrum (higher expansion velocity than supernovae)
ULTIMATE:
IR survey for GW sources

- Survey for ~10 deg$^2$
  - 24 mag depths (10 min)
  - 150 pointing (FOV 0.07 deg$^2$)
    => 25 hr ~ 2.5 nights

- Spectroscopy w/ AO
  (multiplicity is not important)

Pros: Great use of wide-field capability
(would be great if even wider)
Cons: WFIRST can also do this
  but ground telescopes are usually more flexible

Wider wavelength coverage is critical
to measure the total luminosity
Replies to the questions

1. Key science in the post-JWST/WFIRST era
   • Identification of GW sources (if not realized by 2020s) and **mass measurement of r-process elements**

2. 1st priority instrument
   • **Wide-field imager** for time-domain science

3. Science w/ GLAO + MOIRCS
   • ~1/7 of what I presented (proportional to FOV)

4. Which survey design
   • “K-only” survey (C) separated into many epochs

5. Options for wide-field imager
   • Wider field of view > pixel scale (in general)
Summary

- Transient science is blooming NOW!
  - PTF, PS1, DECam, HSC, ZTF, LSST, and WFIRST...
- Nearby supernovae
  - Do all massive stars explode?
  - IR blank-field transient survey
    ~ “K-band only” survey split into >50 epochs
- High-redshift supernovae
  - SN counting => IMF at high-z Universe
  - IR deep transient survey
    ~ “K-band only” survey split in to ~10 epochs
- Gravitational wave sources
  - NS merger as possible origin of r-process elements
  - ToO transient surveys & spectroscopy