Dust Reverberation of AGNs and Its Cosmological application

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Outline

• AGN distance based on the dust reverberation (torus RM)
  – Dust sublimation
  – An old dust lag-luminosity relation

• Recent results from the MAGNUM project
  – A torus RM survey for nearby 17 Seyfert galaxies
  – The dust lag-luminosity relation
  – The Hubble diagram based on the torus-RM distances

• Future progress on the torus-RM cosmology
  – Uncertainties in the torus-RM distance and possible solutions
  – Extension to higher redshifts
Dust in the innermost region of the torus

- **The sublimation of the dust grains**
  - The dust is directly illuminated by the radiation from the accretion disk.
  - As the dust is closer to the accretion disk, its temperature becomes higher.
  - The dust sublimates when it locates too close to the accretion disk. \( T_{\text{sub}} \approx 1800 \text{ K} \) for graphite grain, \( 1500 \text{K} \) for silicate grain
- **Inner radius of the dust torus \((r_{\text{in}})\)**
  - The dust grain is heated up to the sublimation temperature \((T_{\text{sub}})\).
  - The equilibrium of the incident and emitted radiation energy is:

\[
\pi a^2 \int Q_\nu \frac{L^\text{AD}_\nu}{4\pi r_{\text{in}}^2} \, d\nu = 4\pi a^2 \int Q_\nu \pi B_\nu(T_{\text{sub}}) \, d\nu
\]

where \( a \) : dust grain size, \( Q \) : absorption coefficient of dust,
\( B \) : Planck function

(see Barvainis 87, Salpeter 77, Huffman 77)
Distance based on the torus RM

• The radius – luminosity relation for the $r_{in}$ of the dust torus
  – Theoretical expectation:
    \[ r_{in} = A(L_{\nu}^{AD})^{0.5} \]
  – The proportional constant $A$ can be determined by the dust sublimation model with the parameters of $Q_\nu$, $L_\nu$, and $T_{sub}$.
    • $L_\nu$: little systematic variation in AGN spectra of different luminosities
    • $Q_\nu$, $T_{sub}$: determined by the properties of dust grain, which will be common in AGNs

• The luminosity distance
  \[ d_L = \left( \frac{L^{AD}}{4\pi f^{AD}} \right)^{0.5} \propto r_{in} \times (f^{AD})^{-0.5} \]
Torus RM (-1990s)

- The dust lag-luminosity relation for the torus-RM distance
  - There were limited number of the torus RM observations. NGC 4151 (Penston + 74); III Zw 2 (Lebofsky & Rieke 80); Fairall 9 (Clavel, Wamsteker, & Glass 89); NGC 3783 (Glass 92); GQ Comae (Sitko+ 93); NGC 4151 (Oknyanskij 93, 99); Mrk 744 (Nelson 96)
  - The correlation was suggested as theoretically expected. Although the number and quality of the dust lag are somewhat limited.
New torus RM project

• The MAGNUM project (Yoshii+ 1995-)
  – A large systematic torus RM survey program was conducted (Yoshii 02; Yoshii, Kobayashi, & TM 03), which aims to
    • Establish the radius-luminosity relation for the dust torus
    • Measure the luminosity distance of AGNs to constrain the cosmological parameters
  – A robotic 2-m telescope dedicated for the optical and near-infrared monitoring observation was built at the Haleakala observatory (Kobayashi, TM+98).
    • The observation was carried out during 2000-2008.
Both the sample size, and the cadence and the photometric accuracy of the light curve were much improved.
The radius-luminosity relation for the dust torus

- Initial result from the MAGNUM project
  - The dust lag is well correlated with the luminosity as expected, while it is only weakly correlated with the black hole mass (TM+04; Suganuma, TM+ 06).

Suganuma, TM+ 06
The filled symbols represent the data from the MAGNUM, the others from the literature.
The radius-luminosity relation for the dust torus

- The torus RM survey for 17 nearby Seyferts (Koshida, TM+ 14)
  - Dust lag:
    The data of whole sample were analyzed systematically.
    - The accretion disk component in the K-band flux was subtracted prior to the lag analysis to estimate the dust lag correctly.
      - It was estimated by extrapolating the simultaneously obtained V-band flux assuming the power-law continuum SED.

![Graph showing the radius-luminosity relation for the dust torus and intraday variation of NGC 4395.](Image)
The radius-luminosity relation for the dust torus

- **The torus RM survey for 17 nearby Seyferts (Koshida, TM+ 14)**
  - Dust lag:
    - The data of whole sample were analyzed systematically
      - The accretion disk component in the K-band flux was subtracted prior to the lag analysis.
      - A conventional CCF+CCCD method and Javelin (Zu+ 11) were used to obtain the dust lag: They showed consistent results.
      - When different good features in the light curves of a target were found in different epochs, dust lag was obtained respectively.
    → 49 dust lags were obtained in total:
      - This was the largest homogeneous data collection of the torus RM.
  - Luminosity:
    - The host-galaxy component in the V-band flux was carefully estimated with high angular resolution images obtained by the HST, and subtracted (Sakata, TM+ 10; see Bentz+ 09,13).
The radius-luminosity relation for the dust torus

- The torus RM survey for 17 nearby Seyferts (Koshida, TM+ 14)

- The observed dust lag clearly correlates with the optical luminosity as expected:
  \[ r_{\text{in}} \propto (L_{\text{opt}})^{0.5} \]

- The dust lag place an upper boundary of the broad emission-line lags (presented by Suganuma, TM+06).
Torus RM for cosmology

• Distance based on the torus RM (Yoshii, TM+14)
  – The dust sublimation model at the innermost dust torus was built.
    
    • $L_\nu$: a power-law SED with $\alpha_\nu = -0.5 \pm 0.2$ (e.g., Vanden Berk+01)
    
    • $Q_\nu$: the absorption coefficient of graphite (Draine & Lee 84,93) with the grain size distribution intermediate between the standard MRN and that for radio-quiet quasars by Gaskell+04.
    
    • $T_{\text{sub}}$: $T_d = 1700 \pm 50$ K from the near-infrared SED of the time-variable flux component (Tomita 05; Tomita, TM+06)

    – The luminosity distances $d_L$ is expressed using the dust lag as follows:
      
      $$d_L = (\Delta t/\text{days}) \times 10^{0.2(m_\nu-A_\nu-k_\nu-14.4)} \ [\text{Mpc}]$$

      or equivalently,

      $$d_L = 2.5 \times \left( \frac{\Delta t}{\text{days}} \right) \left( \frac{f_\nu}{\text{mJy}} \right)^{-0.5} \ [\text{Mpc}]$$

      (when $A_\nu=0$, $k_\nu=0$)
Torus RM for cosmology

- The Hubble diagram (Yoshii, TM+ 14)
  - The luminosity distances of 17 Seyfert galaxies at z<0.04 were estimated based on the dust sublimation model using the dust lag (Koshida+14) to make a Hubble diagram.

\[
\begin{align*}
\text{Recession Velocity (km s}^{-1}) & \quad \text{Distance (Mpc)} \\
\hline
1000 & 10 \\
10000 & 100
\end{align*}
\]

The best-fit Hubble constant based on the torus-RM distance:

\[ H_0 = 73 \pm 3 \text{ (random) km/s/Mpc} \]

Consistent with the Cepheid distance scale (Freeman+ 01)
Uncertainties in the torus RM distance

- Intrinsic scatter in the dust lag-luminosity relation

- Target to target variation around the best-fit dust lag-luminosity relation: $\sigma_{\text{lag}} \approx 0.13$ dex (Koshida, TM+ 14)

- Possible origins:
  - internal extinction
  - accretion disk SED
  - delayed response of the dust lag change
  - dust temperature
  - torus geometry
  - mass accretion rate
Time variation of the dust lag

- The dust lag becomes larger when the AGN becomes brighter?

- If the inner radius of the dust torus strictly follows $r_{\text{in}} = A(L_{\nu}^{\text{AD}})^{0.5}$ at any time, the dust lag becomes larger when the AGN becomes brighter, tracking on the trend of the global dust lag-luminosity relation $\rightarrow$ would not lead to the intrinsic scatter of the relation.

But NOT
Time variation of the dust lag

- **Delayed response of the dust lag change**
  - The inner radius of the dust torus did NOT respond instantaneously according to the flux change of the accretion disk
  - torus RM: Koshida, TM+09; Oknyanskij+ 14; Schnulle+13, 15
  - Interferometry: Pott+ 10; Kishimoto+ 11, 13.
An origin of uncertainty in the torus RM distance

- **Delayed response of the dust lag change**
  - It will lead to a significant scatter for the dust lag-luminosity relation. (Koshida, TM+ 14; Schnulle+ 15)
Possible solution to reduce uncertainties in the torus RM distance

- **Temperature variation of the dust emission in near-infrared**
  - Schnulle+ 15 measured $T_d$ for NGC 4151 in 2010-2014.
    - $T_d < 1500$ K, which is lower than the dust sublimation temperature.
    - The hot dust located beyond the sublimation radius.
    - $T_d$ changed in time: It closely tracked the accretion disk flux variation in short timescales.

![Graph showing temperature variation](image)
Possible solution to reduce uncertainties in the torus RM distance

- **Temperature variation of the dust emission in near-infrared**
  - The dust lags were larger than the global dust lag-luminosity relation for NGC 4151 in 2000-2008 → $T_d$ might be lower than the ensemble value.
  - If the model parameters for an individual target can be determined observationally (the SED shape of $L^A_D$, $T_d$, $\alpha$, etc.), the uncertainties in the torus-RM distance will be reduced (Yoshii, TM+ 14).

→ The torus RM distance becomes smaller for lower $T_d$
Extension to higher redshifts

- **Observations of higher-redshift targets**
  - The emission in shorter wavelengths would be more contributed by higher temperature of dust, closer to the accretion disk, which would lead to the inter-band time lags in the dust torus emission.
  - For the target at higher redshift,
    - The dust lag should be corrected for the inter-band time lags according to the target redshift.
    - The accretion disk emission contributes larger for shorter wavelengths, and it also should be subtracted properly.
Extension to higher redshifts

- **Inter-band time lag in the dust torus emission**
  - According to the dust sublimation radius by Barvainis 87,
    \[
    r_1 = 1.3L_{uv,46}^{1/2} T_{1500}^{-2.8} \text{ pc}
    \]
  - \(\Delta t (J) / \Delta t (K) = 0.2\) and \(\Delta t (H) / \Delta t (K) = 0.45\), if \(T \propto \lambda^{-1}\)
  - Fortunately, the inter-band dust lag would be not so large based on the multi-band torus RM.
    (Tomita, TM+ 06; Pozo-Nunez+ 14, 15; Oknyanskij+ 15; Schnulle+ 15).
  - But some AGNs show relatively large inter-band dust lag (Oknyanskij+ 15 and references therein)
  - Further study is needed.
    Pozo-Nunez+ 14 WPVS48
    \(\Delta t (B-K)=71\) days, \(\Delta t (B-J)=64\) days

\[
\begin{array}{c}
\text{Day \ after \ MJD \ 56386 (4.4.2013)} \\
0 & 10 & 20 & 30 & 40 & 50 \\
\text{Normalized flux density} \\
0.95 & 1.00 & 1.05 & 1.10 \\
\text{J} & \text{K} \\
\end{array}
\]
Extension to higher redshifts

- **Estimation of the host galaxy flux**
  - The host-galaxy flux should be subtracted for the torus-RM distance.

- **Spectral variability of the optical continuum emission**
  - Sakata, TM+ 10 presented that the multi-epoch flux in any 2 different bands showed a very tight linear correlation (the data come from the MAGNUM monitor).
  - They also estimated the host galaxy flux using the HST images, and found that the host-galaxy flux located on the fainter extension of the straight line.
Extension to higher redshifts

- Estimation of the host galaxy flux from the monitoring data
  - The intersection of the regression line fitted to the flux data and the line represents the host galaxy color in the flux-flux diagram indicates the host galaxy fluxes (Choloniewski+ 81; Winkler+ 92; Winkler 97; Sakata, TM+ 10; Pozo-Nunez+ 14, 15).
Summary

- **Sublimation of dust**: a key for the torus-RM distance.
- **Results from the MAGNUM project**
  - The best dust lag-luminosity relation to date
  - $H_0 = 73 \text{ km/s/Mpc}$ based on the torus-RM distance
- **Future progress in the torus-RM cosmology**
  - Refinement of the torus RM distance
    - The delayed response of the dust-lag change to the flux variation of the accretion disk is a significant source of intrinsic scatter of the dust lag-luminosity relation.
    - Measuring $T_d$ and other observational parameter may help.
    - (Calibration of the torus-RM distance: coming soon)
  - Extension to higher redshift
    - Inter-band time lag in the torus emission should be corrected.
    - Estimation of the host-galaxy flux from the monitoring data.