New Frontiers in Black Hole Astrophysics
Proceedings IAU Symposium No. 324, 2016
Andreja Gomboc, ed.

doi:10.1017/S1743921317000734

A Statistical Method for Detecting Gravitational Recoils of Supermassive Black Holes in Active Galactic Nuclei

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Abstract. We propose an observational test for gravitationally recoiling supermassive black holes in active galactic nuclei, based on a positive correlation between the velocities of black holes relative to their host galaxies, $|\Delta v|$, and their obscuring dust column densities, $\Sigma_{\rm dust}$, both measured along the line of sight. Our findings using a set of toy models implemented to a Monte Carlo simulation imply that models of the galactic centre and of recoil dynamics can be tested by future observations of the potential $\Sigma_{\rm dust}$–$|\Delta v|$ correlation. We have also found that the fraction of obscured quasars decreases with $|\Delta v|$, for which the predicted trend can be compared to the observed fraction of type II quasars, and can further test combinations of models we may implement.

Keywords. black hole physics, galaxies: active, galaxies: nuclei, methods: statistical

1. Introduction

Numerical simulations of black hole binary mergers (see, e.g. Healy *et al.* 2014 and references therein) suggest that merger remnant supermassive black holes (SMBHs) in galactic centres receive a recoil velocity of typically several hundred of km/s due to highly anisotropic gravitational-wave emission in the final merger phase. Taking into account the spatial distribution of mass in the galactic centre region, and corresponding dynamical friction, this means that the SMBH can engage in a damped oscillating motion (Madau & Quataert 2004, Tanaka & Haiman 2009) with an amplitude comparable to, or exceeding the $\mathcal{O}$(10-100 pc) size of the optically thick dusty molecular torus ("dust torus") believed to be surrounding galactic centres (for an overview, see Hönig 2008). As accreting material can stay gravitationally bound to the moving SMBH, and thus the SMBH can remain active for $10^7 - 10^8$ yrs after the merger event (e.g. Loeb 2007), kinematic and spatial signatures of the recoil could be found in the spectra of quasars (QSOs; see, e.g. Bonning *et al.* 2007, Komossa 2012, Blecha *et al.* 2016). These signatures could confirm the gravitational recoil of merger remnant SMBHs, and could probe models of the process and of the galactic centre region.

We propose that in the presence of dust tori obscuring galactic nuclei, the gravitational recoil of active merger remnant SMBHs should introduce a positive correlation between dust column mass densities along the line-of-sight ($\Sigma_{\rm dust}$) and magnitudes of line-of-sight peculiar velocities of SMBHs relative to their host galaxies ($|\Delta v|$). Using a selected combination of models of gravitational recoil, SMBH trajectories, and obscuring dust tori, in Raffai *et al.* (2016) we have demonstrated the feasibility of detecting this $\Sigma_{\rm dust}$–$|\Delta v|$ correlation with simulating random observations of recoiled QSOs. We have also

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calculated the fraction of QSOs obscured by their dust tori, $\mathcal{F}_{\rm obs}(|\Delta v|)$, which, compared to the observed fraction of type II (i.e. obscured) QSOs could provide an independent test for a chosen combination of models. In this paper we highlight our findings presented in details in Raffai *et al.* (2016), and propose an observational method to find the $\Sigma_{\rm dust}$–$|\Delta v|$ correlation using the SDSS-DR12 QSO Catalog (Pâris *et al.* 2016).

2. Black Hole Dynamics and Torus Model

We adopted the analytical formulae given in eq. (4) of Baker *et al.* (2008) to construct the distribution of recoil velocity magnitudes, $v_{\rm recoil}$. We calculated $v_{\rm recoil}$ for a given pair of masses ($m_{1,2}$) and dimensionless spin vectors of the merging SMBHs ($\vec{\alpha}_{1,2}$). For simplicity, we first assigned each merging SMBH one of two observed $|\vec{\alpha}_{1,2}|$ populations (see Reynolds 2013) with equal probability, and then drew a random $|\vec{\alpha}_{1,2}|$ value from the corresponding $\vec{\alpha}_{1,2}$ interval. The directions of spin vectors were chosen independently from a uniform distribution covering a whole sphere. We randomised pairs of masses from the SMBH mass function given in Aller & Richstone (2002), downscaled both mass values by a factor of two, and used them as values for m_1 and m_2. We chose the mass of the merger remnant as $M = m_1 + m_2$.

Using the calculated set of $v_{\rm recoil}$'s with uniformly distributed random directions, we simulated the resulting SMBH trajectories based on the model presented in Madau & Quataert (2004). This model assumes that the SMBH is embedded in a spherical stellar bulge, and is decelerated by dynamical friction. We simulated the trajectories with a $\Delta t = 10^3$ yr time resolution up to a randomly picked final time $T \in [\Delta t, 3 \times 10^4 \Delta t]$. The position, velocity, and Δv of the SMBH in its final state were calculated and stored, as if they were results of a QSO observation made at a random time during the QSO activity after the recoil.

We implemented a hydrostatic model of smooth dust tori presented by Schartmann *et al.* (2005). The dust torus is assumed to form from gas released through stellar winds and ejection of planetary nebulae in the nuclear star cluster. Schartmann *et al.* treat the torus as a continuous medium characterised by the density distribution $\rho_{\rm d}$ (see their eq. 8). The effective potential created by the central SMBH and the angular momentum distribution in the stellar core makes $\rho_{\rm d}$ axisymmetric around the galactic centre.

The density distribution of a torus in this model is fully determined by two parameters: the mass of the nuclear star cluster, M_*, and the mass of the central SMBH, M. Consistently with observations presented in Leigh *et al.* (2012), we chose masses of the nuclear star clusters $M_* = 10^{5+\beta} M_\odot$, where β was drawn from a uniform distribution in the range $\beta \in [0, 4]$. For details about how other parameters of the tori were derived from M_* and M, check Raffai *et al.* (2016).

Using the random values of M_* and M, we calculated $\rho_{\rm d}$ for each torus. In our simulation, only the dust column mass density, $\Sigma_{\rm dust}$, was recorded as the final output, which was calculated by numerically integrating $\rho_{\rm d}$ along the line-of-sight from each SMBH position to the observer for a randomly oriented torus.

3. Results

We simulated a total number of 2.5×10^5 random observations of recoiling QSOs. We have calculated Pearson's r between $\Sigma_{\rm dust}$ and $\log_{10}(|\Delta v|)$ for these QSOs, restricted to various ranges of $|\Delta v|_{\rm min} \leqslant |\Delta v| \leqslant |\Delta v|_{\rm max}$. We have found that obscured QSOs with $|\Delta v| < 5$ km/s show no correlation between their $\Sigma_{\rm dust}$ and $\log_{10}(|\Delta v|)$ values ($r_{<5} \simeq 0$, and the corresponding p–value for the hypothesis of no correlation is $p \simeq 0.95$), while

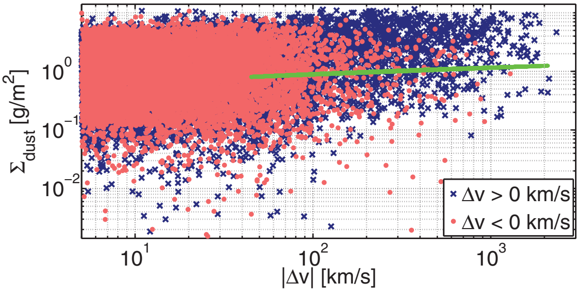

Figure 1. $\Sigma_{\rm dust}$ *vs.* $|\Delta v|$ for the 17,157 obscured QSOs with $|\Delta v| \geqslant 5$ km/s. Receding QSOs are shown by blue crosses, while approaching QSOs are shown by red solid circles. We also show the $\Sigma_{\rm dust}\,(\log_{10}(|\Delta v|)) = (1.7 \pm 0.1)\ \ {\rm g/m^2} \times (\log_{10}(|\Delta v|/[1\ {\rm km/s}])) - (1.3 \pm 0.2)\ \ {\rm g/m^2}$ curve (green solid line) we obtained by fitting $\Sigma_{\rm dust}$ versus $\log_{10}(|\Delta v|)$ values for obscured QSOs with $|\Delta v| \geqslant 45$ km/s.

QSOs with $|\Delta v| \geqslant 5$ km/s show a significant correlation, with $r_5 = 0.22 \pm 0.01$ and $p \simeq 0$. r increases with $|\Delta v|_{\rm min}$ until it reaches its maximum at $|\Delta v|_{\rm min} = 45$ km/s with $r_{45} = 0.28 \pm 0.02$. Allowing $|\Delta v|_{\rm min}$ and $|\Delta v|_{\rm max}$ to vary simultaneously does not change the result that r is the highest for the 3,824 obscured QSOs with $|\Delta v| \geqslant 45$ km/s.

We show $\Sigma_{\rm dust}$ *vs.* $|\Delta v|$ in the subsample of 17,157 obscured QSOs with $|\Delta v| \geqslant 5$ km/s in Figure 1, and indicate whether they are moving away from ($\Delta v > 0$, shown as blue crosses) or towards ($\Delta v < 0$, shown as red full circles) the observer. Receding QSOs are slightly more common than the approaching cases, and $\Sigma_{\rm dust}$ values of the receding QSOs also tend to be higher, especially when the velocity offset is large ($|\Delta v| \geqslant 100$ km/s), This is because receding QSOs are more likely to be found behind, rather than in front of the tori.

Allowing uncorrelated uncertainties on the observational measurements of $\Sigma_{\rm dust}$ and $|\Delta v|$ reduces the statistical significance of a correlation between them, and thus increase the number of QSOs required for a detection. We repeated our analysis after adding a Δv component drawn from a Gaussian distribution with a standard deviation of $\sigma_{\Delta v}$ to the velocity offset of each simulated QSO. We measured the expectation value of Pearson's r ($\langle r \rangle$) between $\Sigma_{\rm dust} > 0$ and $|\Delta v|$ in 1,000 randomly drawn sets of N QSOs from the $|\Delta v| \geqslant 45$ km/s subset, and determined the minimum number $N_{\rm min}$ of QSOs required to infer $r > 0$ with 3σ significance 95% of the time. As expected, the number of QSOs required to detect a correlation increases monotonically with $\sigma_{\Delta v}$, rising to $N_{\rm min} = 3,560$ for the $\Sigma_{\rm dust}$–$|\Delta v|$ correlation and for $\sigma_{\Delta v} = 100$ km/s; this is more than an order of magnitude increase over the $N_{\rm min} = 260$ in the idealised case for the $\Sigma_{\rm dust}$–$\log_{10}(|\Delta v|)$ correlation without any velocity-offset error. $\langle r \rangle$ decreases monotonically with $\sigma_{\Delta v}$, reaching $\langle r \rangle = 0.091 \pm 0.016$ for the $\Sigma_{\rm dust}$–$|\Delta v|$ correlation and for $\sigma_{\Delta v} = 100$ km/s. This is a decrease from the $\langle r \rangle = 0.28 \pm 0.02$ in the idealised case for the $\Sigma_{\rm dust}$–$\log_{10}(|\Delta v|)$ correlation by a factor of three. We also evaluated the impact of random Gaussian errors in $\Sigma_{\rm dust} > 0$, and we have found that realistic values of such errors have a very small effect on the $\Sigma_{\rm dust}$–$\log_{10}(|\Delta v|)$ correlation and thus can be neglected.

Finally, we have studied the fraction of obscured QSOs within the whole sample of QSOs, $\mathcal{F}_{\rm obs}(|\Delta v|)$. We have found that this fraction decreases monotonically with $|\Delta v|$ from $\mathcal{F}_{\rm obs}(< 10\ {\rm km/s}) \gtrsim 0.8$ to $\mathcal{F}_{\rm obs}(> 10^3\ {\rm km/s}) \lesssim 0.4$ (for details, see Figure 11. in Raffai *et al.* 2016). This result can be compared in the future to the observed fraction of obscured (e.g. type II) QSOs, which can potentially provide an independent test for a chosen combination of recoil, trajectory, and dust tori models.

4. Future Work

We propose to use the SDSS-DR12 QSO (DR12Q) catalog (Pâris *et al.* 2016) to perform a search for the correlation between $\Sigma_{\rm dust}$ and $|\Delta v|$. The DR12Q catalog contains data on nearly 300,000 QSOs, for which the BOSS optical spectra are also publicly available. We propose to use the $(g-i)$ color excess of QSOs $(\Delta(g-i))$ as a quantity that is believed to strongly correlate with $\Sigma_{\rm dust}$ (see e.g. Ledoux *et al.* 2015). $\Delta(g-i)$ is defined as the difference in the Galactic extinction corrected $(g-i)$ color for the QSO and that of the mean of the QSOs at that redshift (see Pâris *et al.* 2016). $\Delta(g-i)$ values for different QSOs are given in the DR12Q catalog, and thus can be used in the analysis as a proxy for $\Sigma_{\rm dust}$.

Broad lines in QSO spectra are thought to arise from high-velocity gas remaining bound to the recoiled SMBH, while narrow lines from the gaseous region left unaffected by the recoil in the galactic centre. The line-of-sight velocity offset of a QSO relative to its host can therefore be estimated as $\Delta v = c(z_{\rm B} - z_{\rm N})(1 + z_{\rm N})^{-1}$ using the redshifts corresponding to centroids of broad spectral lines $(z_{\rm B})$, relative to those of narrow lines $(z_{\rm N})$ (see e.g. Bonning *et al.* 2007). We propose to use the BOSS spectra of DR12 QSOs and the method described in Greig *et al.* (2016) to fit both narrow and broad line profiles to the following spectral lines: CIV (λ1549Å), Hβ (λ4863Å), and OIII (λ5007Å). We will then use the most optimal combination of these line profiles to obtain $z_{\rm B}$ and $z_{\rm N}$ values and estimate Δv for the highest possible number of DR12 QSOs.

We will report on the findings of our observational search in a follow-up paper to be published in the near future.

Acknowledgments

Péter Raffai is grateful for the support of the Hungarian Academy of Sciences through the “Bolyai János” Research Scholarship programme. Bence Bécsy was supported by the Hungarian Templeton Program that was made possible through the support of a grant from Templeton World Charity Foundation, Inc. We also acknowledge financial support from the NASA Astrophysics Theory Program under grant #NNX11AE05G (to ZH) and from OTKA under grant no. 101666 (to ZF).

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