

Comparing the Galactic Center to the nucleus of M31

1. Observations

1. M31 appears to harbor a supermassive black hole with $M_{\bullet} = (1.1 - 2.3) \times 10^8 M_{\odot}$ (~ 3 times larger than the value inferred from the $M_{\bullet} - \sigma$ relation; GC SMBH is ~ 3 times smaller).

2. There are three distinct nuclear sources designated P1, P2 and P3.

3. P1 and P2 have similar stellar characteristics (spectral type K, metal-rich stars) while P3 contains primarily early-A to late-B stars.

4. The favored model for the triple nucleus is two nested disks: a circular disk (P3, $r \sim 0.8$ pc) around the SMBH nested within a larger eccentric disk (P1 and P2, $r \sim 8$ pc). Other alternatives are 1) dust obscuration (asymmetry is there in the infrared as well, however) and 2) P1 and P2 are separate clusters (but $t_{df} \sim 10^8$ yr at their 1.8 pc separation).

5. Properties of the eccentric disk:

1) P1 is bright because the stars linger at apapsis there, and P2 is a combination of disk stars with smaller semimajor axes and stars with periapsis near P2 and apapsis near P1.

2) Models in which the disk is nonaligned ($i \sim 55^{\circ}$) with the M31 galactic disk ($i \sim 38^{\circ}$) provide better fits to the data.

3) Asymmetric rotation curve. Measured rotation velocities $\sim 200 \text{ km s}^{-1}$, dispersions $\sim 300 \text{ km s}^{-1}$.

4) Peiris & Tremaine (2003) accurately predict the higher resolution results of Bender et al (2005).

6. Properties of P3 disk:

1) Coplanar with and rotates in the same sense as the eccentric disk.

2) Symmetric rotation curve. Measured rotation velocities $\sim 600 \text{ km s}^{-1}$, dispersions up to $\sim 1000 \text{ km s}^{-1}$.

7. Liu & Melia (2001, ApJ 550): The power at 3.6 cm is 1/3 that of Sgr A*, whereas the X-ray luminosity is thousands of times greater. Helfer et al (2003, ApJS 145): CO emission is well below the average for nearby galaxies.

2. Characteristic Scales

$$M_6 \equiv 10^6 M_\odot \quad M_8 \equiv 10^8 M_\odot \quad (1)$$

$$R_S = \frac{2GM_\bullet}{c^2} \sim 10^{-7} M_6 \text{ pc} \sim 10^{-5} M_8 \text{ pc} \quad (2)$$

$$r_{Q=1} \sim 0.01 \text{ pc} \quad (\alpha \sim 0.3) \quad (3)$$

$$\dot{M}_E = \frac{4\pi G M_\bullet}{\kappa_{e.s.c}} = 0.2 M_6 M_\odot \text{ yr}^{-1} = 20 M_8 M_\odot \text{ yr}^{-1} \quad (4)$$

$$t_{acc} = \frac{M_\bullet}{\epsilon \dot{M}_E} \sim 5 \times 10^7 \epsilon_{0.1}^{-1} \text{ yr} \quad (5)$$

$$t_{visc} = \alpha^{-1} \Omega^{-1} \left(\frac{M_\bullet}{M_{disk}} \right)^2 \sim 10^4 M_6^2 \Omega^{-1} \sim 10^2 M_8^2 \Omega^{-1} \quad (6)$$

$$r_{t\star} = R_\star \left(\frac{M_\bullet}{M_\star} \right)^{1/3} \sim 10^{-6} M_6^{1/3} \text{ pc} \sim 5 \times 10^{-6} M_8^{1/3} \text{ pc} \quad (7)$$

$$r_{coll} = R_\star \left(\frac{M_\bullet}{M_\star} \right) \sim 0.1 M_6 \text{ pc} \sim 10 M_8 \text{ pc} \quad (8)$$

$$R_{bh} \sim 1 M_6 \text{ pc} \sim 20 M_8 \text{ pc} \quad (9)$$

$$\rho_t = \frac{M_\bullet}{r^3} \sim 10^6 M_6 r_{\text{pc}}^{-3} M_\odot \text{ pc}^{-3} \sim 10^8 M_8 r_{\text{pc}}^{-3} M_\odot \text{ pc}^{-3} \quad (10)$$

$$r_{t,cluster} = \left(\frac{M_\bullet}{\rho} \right)^{1/3} \sim 2 M_6^{1/3} \text{ pc} \sim 10 M_8^{1/3} \text{ pc} \quad (\rho \sim 10^5 M_\odot \text{ pc}^{-3}) \quad (11)$$

$$r_{t,cloud} = \left(\frac{M_\bullet}{m_H n} \right)^{1/3} \sim 20 M_6^{1/3} \text{ pc} \sim 100 M_8^{1/3} \text{ pc} \quad (n \sim 10^6 \text{ cm}^{-3}) \quad (12)$$

3. Star Formation

As in the GC, there are two viable models for the formation of the eccentric disk:

1. $10^6 M_\odot$ stellar cluster disrupted by tidal shear (but $P1+P2 \sim 10^7 M_\odot$)
2. Formation in an accretion disk.

Little work has been done to explain the origin of P3. Best fitting stellar population model for P3: 200 ± 50 Myr starburst, 15,000 stars (Salpeter IMF) with total mass $4200 M_\odot$ (original mass $5200 M_\odot$, $10^6 M_\odot$ gas required). A primary difference between P3 and the S stars is that outer extent of the former lies outside the $Q = 1$ radius, so transport may not be required, although it is not clear why the stellar properties should be so different from P1 and P2 if they formed out of the same disk.

From Rauch & Tremaine (1996, NA 149), at $r \sim 0.4$ pc in M31 (the location of P3), $t_r \sim 10^{12}$ and $t_{rr} \sim 2 \times 10^{10}$, with $M_\star \sim 0.002 M_\bullet$. This implies that a disk configuration is stable.

$$\frac{t_{rr}}{t_r} \sim 7 \frac{M_\star}{M_\bullet} ; \quad t_r \sim 4 \times 10^{10} \frac{1}{\ln N_\star} \left(\frac{M_\bullet}{M_\star} \right) \left(\frac{M_\bullet}{10^8 M_\odot} \right)^{1/2} \left(\frac{M_\odot}{m_\star} \right) \left(\frac{r}{1 \text{ pc}} \right)^{3/2} \text{ yr} \quad (13)$$

4. Massive Perturbers

1. Massive objects such as GMCs and clusters can increase the two-body relaxation time by orders of magnitude.

- 1) If the massive perturbers dominate the scattering but not the dynamics:

$$\sqrt{\frac{N_\star}{N_{MP}}} \ll \frac{m_{MP}}{m_\star} \ll \frac{N_\star}{N_{MP}} \rightarrow \frac{t_{r,MP}}{t_{r,\star}} \sim \frac{m_\star^2 N_\star}{m_{MP}^2 N_{MP}} \sim \frac{m_\star M_\star}{m_{MP} M_{MP}} \quad (14)$$

- 2) If the massive perturbers dominate the scattering *and* the dynamics:

$$\sqrt{\frac{N_\star}{N_{MP}}} \ll \frac{N_\star}{N_{MP}} \ll \frac{m_{MP}}{m_\star} \rightarrow \frac{t_{r,MP}}{t_{r,\star}} \sim \frac{N_{MP}}{N_\star} \quad (15)$$

2. Perets, Hopman & Alexander (2005) estimate the improvement to be a factor of $10^2 - 10^5$ in the GC.

3. Melchior et al (2000, MNRAS 312) estimate $N_{MP} \sim 250$ clouds at a radius of 50 pc with a total mass of $M_{MP} \sim 10^4 M_\odot$.