22. The Nearest Galaxies - the Local Group

The following table summarizes the basic properties of the nearest galaxies. As of this writing, the Local Group of galaxies consists of about 40 members. More members are likely, however, as increasingly more sensitive surveys probe the sky for nearby faint dwarfs. Therefore, this table should not be regarded as a complete census of our galaxian neighborhood, especially at the faint end.

Dynamical masses have been calculated for most of the Local Group systems. These estimates are based on either the gas rotation velocities or the stellar velocity dispersions in the galaxies (see Endnote 16). They range from close to a trillion \((10^{12})\) solar masses for M31 and the Milky Way, to less than a few million Suns for the faintest dwarf ellipticals. The corresponding mass-to-light ratios are greatest for the faintest dwarfs, indicating that they harbor the highest proportions of dark matter.

**Table E6: Selected Galaxies of the Local Group**

*(in order of decreasing luminosity [increasing absolute magnitude, \(M(B)\)])*

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>RA(hr:min)</th>
<th>Dec (°: ′)</th>
<th>Distance (light-yrs)</th>
<th>(m(B)) (mags)</th>
<th>(M(B)) (mags)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M31</td>
<td>SbI-II</td>
<td>00:42.73</td>
<td>+41:16.1</td>
<td>2.5 x 10⁶</td>
<td>4.4</td>
<td>−21.6</td>
</tr>
<tr>
<td>Galaxy</td>
<td>SBbcI-II</td>
<td>17:45.67</td>
<td>−20:00.5</td>
<td>2.7 x 10⁴</td>
<td></td>
<td>−20.5?</td>
</tr>
<tr>
<td>M33</td>
<td>ScII-III</td>
<td>01:33.85</td>
<td>+30:39.6</td>
<td>2.7 x 10⁶</td>
<td>6.3</td>
<td>−19.1</td>
</tr>
<tr>
<td>LMC</td>
<td>SBmIII</td>
<td>05:23.57</td>
<td>−69:45.4</td>
<td>1.6 x 10⁵</td>
<td>0.6</td>
<td>−18.4</td>
</tr>
<tr>
<td>SMC</td>
<td>ImIV-V</td>
<td>00:52.73</td>
<td>−72:49.7</td>
<td>1.9 x 10⁵</td>
<td>2.8</td>
<td>−17.0</td>
</tr>
<tr>
<td>NGC 205</td>
<td>S0/E5p</td>
<td>00:40.37</td>
<td>+41:41.4</td>
<td>2.7 x 10⁶</td>
<td>8.7</td>
<td>−16.0</td>
</tr>
<tr>
<td>M32</td>
<td>E2</td>
<td>00:42.70</td>
<td>+40:51.9</td>
<td>2.6 x 10⁶</td>
<td>9.1</td>
<td>−15.8</td>
</tr>
<tr>
<td>NGC 3109</td>
<td>SmIV</td>
<td>10:03.12</td>
<td>−26:09.5</td>
<td>4.1 x 10⁶</td>
<td>10.4</td>
<td>−15.2</td>
</tr>
<tr>
<td>IC10</td>
<td>Im</td>
<td>00:20.42</td>
<td>+59:17.5</td>
<td>2.7 x 10⁶</td>
<td>12.9</td>
<td>−15.2</td>
</tr>
<tr>
<td>NGC 6822</td>
<td>ImIV-V</td>
<td>19:44.93</td>
<td>−14:48.1</td>
<td>1.6 x 10⁶</td>
<td>9.8</td>
<td>−14.8</td>
</tr>
<tr>
<td>NGC 147</td>
<td>dE5/dSph</td>
<td>00:33.20</td>
<td>+48:30.5</td>
<td>2.4 x 10⁶</td>
<td>10.3</td>
<td>−14.8</td>
</tr>
<tr>
<td>NGC 185</td>
<td>dE3p/dSph</td>
<td>00:38.97</td>
<td>+48:20.2</td>
<td>2.0 x 10⁶</td>
<td>10.0</td>
<td>−14.7</td>
</tr>
<tr>
<td>IC 5152</td>
<td>SdmIV-V</td>
<td>22:02.70</td>
<td>−51:17.7</td>
<td>5.2 x 10⁶</td>
<td>11.5</td>
<td>−14.5</td>
</tr>
<tr>
<td>IC 1613</td>
<td>ImV</td>
<td>01:04.90</td>
<td>+02:08.0</td>
<td>2.3 x 10^6</td>
<td>10.2</td>
<td>−14.2</td>
</tr>
<tr>
<td>-----------</td>
<td>--------</td>
<td>----------</td>
<td>----------</td>
<td>------------</td>
<td>------</td>
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</tr>
<tr>
<td>Sextans A</td>
<td>ImV</td>
<td>10:11.10</td>
<td>−04:42.5</td>
<td>4.7 x 10^6</td>
<td>11.7</td>
<td>−14.2</td>
</tr>
<tr>
<td>WLM</td>
<td>ImIV-V</td>
<td>00:01.97</td>
<td>−15:27.8</td>
<td>3.0 x 10^6</td>
<td>11.0</td>
<td>−13.9</td>
</tr>
<tr>
<td>Sagittarius</td>
<td>dlm/dSph</td>
<td>18:55.05</td>
<td>−30:28.7</td>
<td>7.8 x 10^4</td>
<td>4.1</td>
<td>−12.8</td>
</tr>
<tr>
<td>Fornax</td>
<td>dE3/dSph</td>
<td>02:39.98</td>
<td>−34:27.0</td>
<td>4.5 x 10^5</td>
<td>8.2</td>
<td>−12.6</td>
</tr>
<tr>
<td>Pegasus</td>
<td>dlm/dSph</td>
<td>23:28.57</td>
<td>+14:44.8</td>
<td>3.1 x 10^6</td>
<td>12.6</td>
<td>−12.3</td>
</tr>
<tr>
<td>SagDIG</td>
<td>dlm</td>
<td>19:29.98</td>
<td>−17:40.7</td>
<td>3.5 x 10^6</td>
<td>13.9</td>
<td>−12.1</td>
</tr>
<tr>
<td>Leo A</td>
<td>dlm</td>
<td>09:59.40</td>
<td>+30:44.7</td>
<td>2.2 x 10^6</td>
<td>12.9</td>
<td>−11.3</td>
</tr>
<tr>
<td>GR8</td>
<td>dlm</td>
<td>12:58.67</td>
<td>+14:13.0</td>
<td>5.2 x 10^6</td>
<td>14.8</td>
<td>−11.2</td>
</tr>
<tr>
<td>And I</td>
<td>dE3/dSph</td>
<td>00:45.72</td>
<td>+38:00.4</td>
<td>2.6 x 10^6</td>
<td>13.5</td>
<td>−11.2</td>
</tr>
<tr>
<td>Leo I</td>
<td>dE3/dSph</td>
<td>10:08.45</td>
<td>+12:18.5</td>
<td>8.1 x 10^5</td>
<td>10.9</td>
<td>−11.1</td>
</tr>
<tr>
<td>And II</td>
<td>dE2/dSph</td>
<td>01:16.45</td>
<td>+33:25.7</td>
<td>1.7 x 10^6</td>
<td>13.3</td>
<td>−10.5</td>
</tr>
<tr>
<td>Sculptor</td>
<td>dE3/dSph</td>
<td>01:00.15</td>
<td>−33:42.5</td>
<td>2.6 x 10^5</td>
<td>8.5</td>
<td>−10.4</td>
</tr>
<tr>
<td>LGS 3</td>
<td>dlm/dSph</td>
<td>01:03.88</td>
<td>+21:53.1</td>
<td>2.6 x 10^6</td>
<td>15.0</td>
<td>−9.9</td>
</tr>
<tr>
<td>DDO 210</td>
<td>dlm/dSph</td>
<td>20:46.77</td>
<td>−12:51.0</td>
<td>2.6 x 10^6</td>
<td>14.9</td>
<td>−9.9</td>
</tr>
<tr>
<td>And III</td>
<td>dE5/dSph</td>
<td>00:35.28</td>
<td>+36:30.5</td>
<td>2.5 x 10^6</td>
<td>14.8</td>
<td>−9.7</td>
</tr>
<tr>
<td>Leo II</td>
<td>dE0/dSph</td>
<td>11:13.48</td>
<td>+22:09.2</td>
<td>6.7 x 10^5</td>
<td>12.6</td>
<td>−9.0</td>
</tr>
<tr>
<td>Tucana</td>
<td>dE/dSph</td>
<td>22:41.83</td>
<td>−64:25.2</td>
<td>2.9 x 10^6</td>
<td>15.7</td>
<td>−8.9</td>
</tr>
<tr>
<td>Carina</td>
<td>dE4/dSph</td>
<td>06:41.62</td>
<td>−50:58.0</td>
<td>3.3 x 10^5</td>
<td>11.5</td>
<td>−8.6</td>
</tr>
<tr>
<td>Draco</td>
<td>dE3/dSph</td>
<td>17:20.32</td>
<td>+57:54.8</td>
<td>2.7 x 10^5</td>
<td>11.8</td>
<td>−7.8</td>
</tr>
<tr>
<td>UrsaMinor</td>
<td>dE5/dSph</td>
<td>15:09.18</td>
<td>+67:12.9</td>
<td>2.1 x 10^5</td>
<td>11.6</td>
<td>−7.6</td>
</tr>
</tbody>
</table>

Notes to table:

(1) Name of galaxy.
(2) Galaxy classification, based mostly on the Hubble-Sandage system. Dwarf ellipticals are designated “dE,” while dwarf irregulars are designated dlm. The dwarf spheroidal classification preferred by many investigators of the Local Group is designated “dSph.” Peculiar morphologies are flagged with a “p.”
(3) Right Ascension (celestial longitude) in units of hours (hrs) and minutes (min), precessed to the 2000.0 epoch.
(4) Declination (celestial latitude) in units of degrees (°) and arcminutes (′), precessed to the 2000.0 epoch.
(5) Distance from the Sun in units of light-years, determined mostly from observations of Cepheid and RR Lyrae variable stars.
(6) Apparent magnitude at $B$-band (440 nm wavelength).
(7) Absolute magnitude at $B$-band, based on apparent magnitude $m(B)$ and the distance (see Technical Notes 2 and 3).

References for table:

23. Nearby Giant Galaxies

In the following table, 30 giant spiral (S), lenticular (S0), and elliptical galaxies (E) in the Local Group and other neighboring groups are listed. These galaxies have been selected for their apparent brightness in the sky (with $m(B) < 10$ mags) and high absolute luminosity (with $M(B) < -19$ mags and corresponding $B$-band luminosity exceeding 3 billion Suns [see Endnote 3]).

Table E7: Selected Giant Galaxies

(in order of increasing distance from the Sun)

<table>
<thead>
<tr>
<th>Name(s) (1)</th>
<th>Type Comment (2)</th>
<th>RA (hr:min Dec (°:′) (3)</th>
<th>Size (′) $m(B)$ (mags) (4)</th>
<th>vel (km/s) Dist. (Mpc) (5)</th>
<th>$A(B)$ (mags) $M(B)$ (mags) (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy</td>
<td>SBbc(rs)I-II “MilkyWay”</td>
<td>17:45.67 -20:00.5</td>
<td>190 x 60 4.4</td>
<td>0.0 0.008</td>
<td>-20.5?</td>
</tr>
<tr>
<td>NGC 224 (M31)</td>
<td>Sb1-II “Andromeda”</td>
<td>00:42.73 +41:16.1</td>
<td>70.8 x 41.7 6.3</td>
<td>670 0.85*</td>
<td>1.7 -21.7</td>
</tr>
<tr>
<td>NGC 598 (M33)</td>
<td>Sc(s)II-III “Pinwheel”</td>
<td>01:33.85 +30:39.6</td>
<td>26.9 x 14.1 7.9</td>
<td>124 3.6*</td>
<td>0.8 -20.8</td>
</tr>
<tr>
<td>NGC 55</td>
<td>Sc (edge-on)</td>
<td>00:15.13 -39:13.2</td>
<td>32.4 x 5.6 8.2</td>
<td>115 2.1</td>
<td>0.9 -19.3</td>
</tr>
<tr>
<td>NGC 3031 (M81)</td>
<td>Sb(r)I-II</td>
<td>09:55.57 +69:04.1</td>
<td>21.9 x 12.3 8.9</td>
<td>2999 3.2*</td>
<td>0.6 -19.2</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>Sc(s)III</td>
<td>07:36.90 +65:35.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


| NGC 253 | Sc(s)  
| (starburst) | 00:47.60  
|           | −25:17.4  
|          | 27.5 x 6.8  
|          | 8.1  
|          | 504  
|          | 2.8  
|          | 0.7  
|          | −19.8  
| NGC 4736  
| (M94) | RSab(rs)  
|        | 12:50.90  
|        | +41:07.17  
|        | 11.2 x 9.1  
|        | 8.9  
|        | 345  
|        | 4.6  
|        | 0.5  
|        | −19.9  
| NGC 6946 | Sc(s)II  
|        | 20:34.85  
|        | +60:09.4  
|        | 11.5 x 9.8  
|        | 9.7  
|        | 336  
|        | 4.5  
|        | 1.5  
|        | −20.1  
| NGC 5236  
| (M83) | SBc(s)II  
|        | 13:37.00  
|        | −29:52.0  
|        | 12.9 x 11.5  
|        | 8.5  
|        | 275  
|        | 4.6  
|        | 0.4  
|        | −20.2  
| NGC 5128  
| (Cen A) | S0+S pec  
| (AGN) | 13:25.48  
|        | −43:01.0  
|        | 25.7 x 20.0  
|        | 7.9  
|        | 251  
|        | 4.6  
|        | 1.27  
|        | −21.7  
| NGC 4826  
| (M64) | Sab(s)II  
|        | 12:56.75  
|        | +21:41.0  
|        | 10.0 x 5.4  
|        | 9.4  
|        | 350  
|        | 4.7  
|        | 0.7  
|        | −19.7  
| NGC 4945 | Sc  
| (edge-on) | 13:05.43  
|        | −49:28.0  
|        | 20.0 x 3.8  
|        | 9.6  
|        | 275  
|        | 4.7  
|        | 1.3  
|        | −20.0  
| NGC 2903 | Sc(s)I-II  
|        | 09:32.17  
|        | +21:29.9  
|        | 12.6 x 6.0  
|        | 9.5  
|        | 472  
|        | 6.3  
|        | 0.6  
|        | −20.1  
| NGC 4258  
| (M106) | Sb(s)II  
| (AGN) | 12:18.95  
|        | +47:18.4  
|        | 18.6 x 7.2  
|        | 8.9  
|        | 520  
|        | 6.7  
|        | 0.9  
|        | −21.2  
| NGC 5055  
| (M63) | Sc(s)II-III  
| “Sunflower” | 13:15.83  
|        | +42:01.7  
|        | 12.6 x 7.2  
|        | 9.3  
|        | 550  
|        | 7.3  
|        | 0.5  
|        | −20.5  
| NGC 5194  
| (M51) | Sbc(s)I-II  
| “Whirlpool” | 13:29.88  
|        | +47:11.9  
|        | 11.2 x 6.9  
|        | 8.6  
|        | 541  
|        | 7.3  
|        | 0.4  
|        | −20.7  
| NGC 5457  
| (M101) | Sc(s)I  
| “Pinwheel” | 14:03.22  
|        | +54:21.0  
|        | 28.8 x 26.9  
|        | 8.2  
|        | 372  
|        | 7.4*  
|        | 0.3  
|        | −21.5  
| NGC 3627  
| (M66) | Sb(s)II-2  
| “Black Eye” | 11:20.25  
|        | +12:59.1  
|        | 9.1 x 4.2  
|        | 9.7  
|        | 593  
|        | 8.0  
|        | 0.8  
|        | −20.6  
| NGC 4631 | Sc  
| (edge-on) | 12:42.08  
|        | +32:32.4  
|        | 15.5 x 2.7  
|        | 9.8  
|        | 606  
|        | 8.0  
|        | 0.9  
|        | −20.6  
| NGC 3521 | Sb(s)II-III  
|        | 11:05.82  
|        | −00:02.0  
|        | 11.0 x 5.1  
|        | 9.6  
|        | 627  
|        | 8.7  
|        | 0.8  
|        | −20.8  
| NGC 6744 | Sbc(r)II  
|        | 19:09.77  
|        | −63:51.3  
|        | 20.0 x 12.9  
|        | 9.2  
|        | 663  
|        | 8.7  
|        | 0.6  
|        | −21.1  
| NGC 1291 | SBa  
|        | 03:17.32  
|        | −41:06.5  
|        | 9.8 x 8.1  
|        | 9.4  
|        | 738  
|        | 10.0  
|        | 0.2  
|        | −20.8  
| NGC 628 | Sc(s)I  
|        | 01:36.70  
|        | 10.5 x 9.5  
|        | 861  
|        | 0.3  
<p>|</p>
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<th></th>
<th></th>
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<td>(M74)</td>
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<td></td>
</tr>
<tr>
<td>NGC 4594</td>
<td>Sa/Sb</td>
<td>12:40:00</td>
<td>8.7 x 3.5</td>
<td>373</td>
<td>0.9</td>
</tr>
<tr>
<td>(M104)</td>
<td>“Sombrero”</td>
<td>-11:37.4</td>
<td>9.3</td>
<td>11.3</td>
<td>-21.9</td>
</tr>
<tr>
<td>NGC 4472</td>
<td>E1/S0</td>
<td>12:29.78</td>
<td>10.2 x 8.3</td>
<td>322</td>
<td>0.0</td>
</tr>
<tr>
<td>(M49)</td>
<td>+07:59.8</td>
<td>9.3</td>
<td>14.7</td>
<td>-21.5</td>
<td></td>
</tr>
<tr>
<td>NGC 4486</td>
<td>E0</td>
<td>12:30.83</td>
<td>8.3 x 6.6</td>
<td>1136</td>
<td>0.0</td>
</tr>
<tr>
<td>(M87)</td>
<td>“Virgo A”</td>
<td>+12:23.6</td>
<td>9.6</td>
<td>14.7</td>
<td>-21.2</td>
</tr>
<tr>
<td>NGC 4649</td>
<td>S0</td>
<td>12:43.67</td>
<td>7.4 x 6.0</td>
<td>1142</td>
<td>0.0</td>
</tr>
<tr>
<td>(M60)</td>
<td>+11:33.1</td>
<td>9.8</td>
<td>14.7</td>
<td>-21.0</td>
<td></td>
</tr>
<tr>
<td>NGC 1068</td>
<td>Sb(rs)II</td>
<td>02:42.68</td>
<td>7.1 x 6.0</td>
<td>1234</td>
<td>0.5</td>
</tr>
<tr>
<td>(M77)</td>
<td>(AGN)</td>
<td>-00:00.9</td>
<td>9.5</td>
<td>16.7</td>
<td>-22.0</td>
</tr>
<tr>
<td>NGC 1316</td>
<td>Sa pec</td>
<td>03:22.70</td>
<td>12.0 x 8.5</td>
<td>1713</td>
<td>0.3</td>
</tr>
<tr>
<td>“Fornax A”</td>
<td>-37:12.5</td>
<td>9.6</td>
<td>22.3</td>
<td>-22.4</td>
<td></td>
</tr>
</tbody>
</table>

Notes to table:
1. Name(s) of galaxy in the New General Catalogue (NGC) and Messier (M) listings.
2. Galaxy classification, based mostly on the Hubble-Sandage system.
3. Proper names and other comments ... (AGN) refers to an active galactic nucleus.
4. Right Ascension (celestial longitude) in units of hours (hrs) and minutes (min), and Declination (celestial latitude) in units of degrees (°) and arcminutes (′), both coordinates precessed to the 2000.0 epoch.
5. Angular dimensions along the major axis (2a) and minor axis (2b), in arcminutes (′).
6. If the galaxy has a thin disk of circular shape, the respective dimensions provide a measure of the galaxy’s inclination (i), such that {cos (i) ñ b/a}.
7. Apparent magnitude at B-band, before correction for foreground extinction by dust.
8. Radial velocity after correction for the peculiar motions of the Sun and Galaxy with respect to the centroid of the Local Group.
9. Distance from the Sun in units of megaparsecs (Mpc), where 1 Mpc = 3.26 x 10^6 light-years. Distances with an asterisk are based on observations of Cepheid variables and subsequent application of the Period-Luminosity relation (see Chapters 7 & 12).
10. Distances of the remaining galaxies are estimated from the measured radial velocity of each galaxy (or associated galaxy group) and application of the Hubble law, where the assumed Hubble constant is H_0 = 75 km/s/Mpc (see Chapters 12 & 15).
11. B-band extinction due to foreground dust in our Galaxy and dust internal to the galaxy itself (the latter extinction is based on the galaxy’s Hubble type and inclination).
12. Absolute magnitude at B-band, based on the extinction-corrected apparent magnitude m_o(B) and the distance (see Technical Notes 2 & 3).

References for table:

### 24. Starbursting and Interacting Galaxies

In the following table, 20 relatively nearby starbursting and interacting galaxies are listed. Their selection has no photometric basis (unlike in Table E7) but is based on their prominence in the scientific literature.

**Table E8. Selected Starbursting and Interacting Galaxies**

*(in order of increasing distance)*

<table>
<thead>
<tr>
<th>Name(s) (1)</th>
<th>Type Comment (2)</th>
<th>RA (hr:min) Dec (°:’) (3)</th>
<th>Size (’) m(B) (mags) (4)</th>
<th>Vel (km/s) Dist (Mpc) (5)</th>
<th>A(B) (mags) M(B) (mags) (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1569 (Arp 210)</td>
<td>SmIIV (starburst)</td>
<td>04:30:82 +64:50.9</td>
<td>3.6 x 1.8 11.9</td>
<td>144 2.2</td>
<td>3.0 −17.8</td>
</tr>
<tr>
<td>NGC 253</td>
<td>Sc(s) (starburst)</td>
<td>00:47:60 −25:17.4</td>
<td>27.5 x 6.8 8.1</td>
<td>504 2.8</td>
<td>0.7 −19.8</td>
</tr>
<tr>
<td>NGC 3034 (M82) (Arp 337)</td>
<td>Amorphous (edge-on) (starburst)</td>
<td>09:55:87 +69:40.8</td>
<td>11.2 x 4.3 9.3</td>
<td>409 3.6</td>
<td>0.7 −19.2</td>
</tr>
<tr>
<td>NGC 4214</td>
<td>SBmII (starburst)</td>
<td>12:15:66 +36:19.6</td>
<td>8.5 x 6.6 10.2</td>
<td>290 3.9</td>
<td>0.1 −17.8</td>
</tr>
<tr>
<td>NGC 5128 (Cen A) (Arp 153)</td>
<td>S0+S pec (merger) (AGN)</td>
<td>13:25:46 −43:01.1</td>
<td>25.7 x 20.0 7.9</td>
<td>251 4.6</td>
<td>0.5 −20.9</td>
</tr>
<tr>
<td>NGC 5194/5 (M51) (Arp 85)</td>
<td>Sc(s)+SB0 (interacting) “Whirlpool”</td>
<td>13:29:88 +47:11.9</td>
<td>11x7,6x5 9.0, 10.5</td>
<td>251 7.3</td>
<td>0.1 −20.5, −19.0</td>
</tr>
<tr>
<td>NGC 5457 (M101) (Arp 26)</td>
<td>Sc(s)I (interacting) “Pinwheel”</td>
<td>14:03:22 +54:21.0</td>
<td>28.8 x 26.9 8.2</td>
<td>372 7.4</td>
<td>0.04 −21.2</td>
</tr>
<tr>
<td>NGC 2685 (Arp 336)</td>
<td>S0 pec (polar ring) “Helix”</td>
<td>08:55:58 +58:44.0</td>
<td>4.5 x 2.3 11.9</td>
<td>1001 13.3</td>
<td>0.3 −19.0</td>
</tr>
<tr>
<td>NGC 3310 (Arp 217)</td>
<td>Sbc(r) pec (starburst)</td>
<td>10:38:76 +53:30.2</td>
<td>3.1 x 2.4 11.2</td>
<td>1073 14.3</td>
<td>0.1 −19.7</td>
</tr>
<tr>
<td>NGC 1068 (M77)</td>
<td>Sb(rs)II (starburst)</td>
<td>02:42:68 7.1 x 6.0 9.5</td>
<td>1234 16.7</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>(Arp 37)</td>
<td>(HII/AGN)</td>
<td>Right Ascension</td>
<td>Declination</td>
<td>21.6</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-------------------</td>
<td>-----------------</td>
<td>-------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>NGC 4038/9</td>
<td>Sc+Sc pec</td>
<td>12:01.88</td>
<td>5x3, 3x2</td>
<td>1391</td>
<td>0.2</td>
</tr>
<tr>
<td>(Arp 244)</td>
<td>(interacting)</td>
<td>−18:51.9</td>
<td>11.2, 11.1</td>
<td>18.5</td>
<td>−20.3, −20.4</td>
</tr>
<tr>
<td>NGC 520</td>
<td>Amorphous</td>
<td>01:24.58</td>
<td>2.2 x 1.1</td>
<td>2350</td>
<td>0.1</td>
</tr>
<tr>
<td>(Arp 157)</td>
<td>(merger)</td>
<td>+03:47.5</td>
<td>12.1</td>
<td>31.3</td>
<td>−20.5</td>
</tr>
<tr>
<td>NGC 7714</td>
<td>SBB(s) pec</td>
<td>23:36.23</td>
<td>1.9 x 1.4</td>
<td>2994</td>
<td>0.2</td>
</tr>
<tr>
<td>(Arp 284)</td>
<td>(interacting)</td>
<td>+02:09.3</td>
<td>13.0</td>
<td>39.9</td>
<td>−20.2</td>
</tr>
<tr>
<td>(Mrk 538)</td>
<td>(HII/AGN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 3690</td>
<td>S+IBm pec</td>
<td>11:28.50</td>
<td>1x1, 2x1</td>
<td>3096</td>
<td>0.1</td>
</tr>
<tr>
<td>(Arp 299)</td>
<td>(interacting)</td>
<td>+58:33.7</td>
<td>11.8, 12.0</td>
<td>41.3</td>
<td>−21.3, −21.1</td>
</tr>
<tr>
<td>(Mrk 171)</td>
<td>(HII/AGN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 7252</td>
<td>RS0(r)</td>
<td>22:20.75</td>
<td>1.9 x 1.6</td>
<td>4759</td>
<td>0.1</td>
</tr>
<tr>
<td>(Arp 226)</td>
<td>(merger)</td>
<td>−24:40.7</td>
<td>12.9</td>
<td>63.4</td>
<td>−21.2</td>
</tr>
<tr>
<td>“Atoms for</td>
<td>Peace”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arp 220</td>
<td>S?</td>
<td>15:34.95</td>
<td>1.5 x 1.2</td>
<td>5473</td>
<td>0.22</td>
</tr>
<tr>
<td>(merger)</td>
<td>(ULIRG)</td>
<td>+23:30.2</td>
<td>13.9</td>
<td>73.0</td>
<td>−20.6</td>
</tr>
<tr>
<td>NGC 4676</td>
<td>Im±SB0/a(s)</td>
<td>12:46.17</td>
<td>2x1, 2x1</td>
<td>6591</td>
<td>0.1</td>
</tr>
<tr>
<td>(Arp 242)</td>
<td>(interacting)</td>
<td>+30:43.6</td>
<td>14.7, 14.4</td>
<td>87.9</td>
<td>−20.1, −20.4</td>
</tr>
<tr>
<td>“Mice”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 6240</td>
<td>Amorphous</td>
<td>16:52.98</td>
<td>2.1 x 1.1</td>
<td>7455</td>
<td>0.3</td>
</tr>
<tr>
<td>(merger)</td>
<td>(ULIRG)</td>
<td>+02:24.0</td>
<td>13.8</td>
<td>99.4</td>
<td>−21.4</td>
</tr>
<tr>
<td>Arp-Madore</td>
<td>Ring</td>
<td>00:37.68</td>
<td>1.1 x 0.9</td>
<td>9057</td>
<td>0.0</td>
</tr>
<tr>
<td>0035-33S</td>
<td>(collision)</td>
<td>−33:43.0</td>
<td>15.2</td>
<td>120.7</td>
<td>−20.2</td>
</tr>
<tr>
<td>“Cartwheel”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mrk 231</td>
<td>Sc(rs)? pec</td>
<td>12:56.24</td>
<td>1.3 x 1.0</td>
<td>12715</td>
<td>0.0</td>
</tr>
<tr>
<td>(HII/AGN)</td>
<td></td>
<td>+56:52.4</td>
<td>14.4</td>
<td>169.5</td>
<td>−21.8</td>
</tr>
</tbody>
</table>

Notes to table:
(1) *Name(s)* of galaxy in the New General Catalogue (NGC), Messier (M), Arp, Arp-Madore (AM), and Markarian (Mrk) listings.
(2) *Galaxy classification*, based mostly on the Hubble-Sandage system. These types are most uncertain for the edge-on and strongly interacting systems.
*Proper names and other comments* ... (HII/AGN) refers to a mix of ionizing starburst activity (HII) and non-stellar nuclear activity (AGN), while (ULIRG) denotes an ultraluminous infrared galaxy, where the infrared luminosity exceeds 10¹² Suns.
(3) *Right Ascension* (celestial longitude) in units of hours (hrs) and minutes (min), and *Declination* (celestial latitude) in units of degrees (°) and arcminutes (′), both coordinates precessed to the 2000.0 epoch.
(4) *Angular dimensions* along the major axis (2a) and minor axis (2b), in arcminutes (′).
Apparent magnitude at B-band, before correction for foreground extinction by dust.
(5) Radial velocity after correction for the peculiar motions of the Sun and Galaxy with respect to the centroid of the Local Group.
Distance from the Sun in units of megaparsecs (Mpc), where 1 Mpc = 3.26 x 10^6 light-years, based mostly on the measured radial velocity of the galaxy (or associated galaxy group) and application of the Hubble law, where the assumed Hubble constant is H₀ = 75 km/s/Mpc (see Chapters 12 & 15).
(6) Extinction at B-band due to foreground dust in our Galaxy.
Absolute magnitude at B-band, based on the extinction-corrected apparent magnitude m₀(B) and the distance (see Technical Notes 2 & 3). This does not include the problematic correction for extinction internal to the galaxy, and hence underestimates the galaxy’s true B-band luminosity.

References for table:
Kennicutt, R. C., Schweizer, F., & Barnes, J. E. 1998, Galaxies: Interactions and Induced Star Formation, Saas-Fee Advanced Course 26, Lecture Notes 1996, Swiss Society for Astrophysics and Astronomy, Berlin, Germany: Springer-Verlag
NASA/IPAC Extragalactic Database (NED) website, <http://nedwww.ipac.caltech.edu>

25. Tidal Action

The dynamic effects of gravitational tides can be witnessed throughout the Universe - from the oceanic tides on Earth, to the rings of icy debris surrounding Saturn, to the tidal bridges and tails of stars flung off interacting galaxies. All of these phenomena can be attributed to gradients of gravitational force across the respective bodies.

In the case of the Earth-Moon system, the Moon’s gravitation is most strongly felt on the side of Earth that is facing the Moon and most weakly felt on the opposite side. This gradient in the gravitational force across the Earth results in the oceans closest to the Moon accelerating towards the Moon by an amount that is greater than that of the Earth’s core. The oceans farthest from the Moon experience the least acceleration, and hence are seen to lag behind the Earth’s core. The net result are two tidally-induced oceanic bulges - one directed towards the Moon, and the other bulging in the opposite direction. As the solid Earth spins underneath these two liquid bulges, each shoreline experiences two high tides per day. The “tails” and “bridges” of stars observed in interacting galaxies can be thought of as tidal bulges run riot.

Further insights on tidal action can be attained by considering how the gradient in gravitational force depends on the gravitating masses and the interacting geometry. From Newton’s “inverse square” law of universal gravitation, the gravitational force can be formulated as

\[ F_G = -\frac{GM_1m}{r^2}, \]
where \( M_1 \) is the mass of the primary body, \( m \) is the mass of a test particle on the secondary body \( M_2 \), \( r \) is the separation between mass centroids, \( G \) is Newton’s constant of universal gravitation, and the negative sign indicates the attractive nature of gravitational force. The gradient in the gravitational force can be derived by taking the spatial derivative of the above formulation, whereby

\[
\frac{dF_G}{dr} = -\frac{2GM_1m}{r^3}.
\]

This tidal gradient varies as the inverse cube of the separation and is directed opposite to that of the gravitational force itself. If one considers the gradient across a particular body of radius \( R_2 \), the corresponding tidal stress \( T \) from core to surface is

\[
T = \Delta F \approx \left( \frac{dF_G}{dR} \right) R_2, \text{ or}
\]

\[
T \approx \left( \frac{2GM_1m}{r^3} \right) R_2,
\]

where the approximation applies only if the size of the secondary body is considerably smaller than the separation between bodies. Serious tidal disruption occurs at the so-called Roche limit, where and when a body’s tidal stress begins to exceed its own gravitational cohesion. Considering the tidal acceleration across such a body yields

\[
a_T = \frac{T}{m} \approx \left( \frac{2GM_1}{r^3} \right) R_2.
\]

Setting the tidal acceleration equal to the body’s self gravity at its surface, such that

\[
a_T = a_G = \frac{GM_2}{R_2^2},
\]

yields

\[
\frac{r^3}{R_2^3} \approx \frac{2M_1}{M_2}, \text{ or}
\]

\[
\frac{r}{R_2} \approx 1.3 \left( \frac{M_1}{M_2} \right)^{\frac{1}{3}}.
\]

A more careful analysis by Edouard Roche in 1850 that allowed for small separations yielded a somewhat higher coefficient of 2.44.

In the case of the Saturnian ring system, the Roche limit can be expressed in terms of the densities involved, such that

\[
r \approx 2.44R_2 \left( \frac{\rho_1 R_1^3}{\rho_2 R_2^3} \right)^{\frac{1}{5}}, \text{ or}
\]

\[
r \approx 2.44R_1 \left( \frac{\rho_1}{\rho_2} \right)^{\frac{1}{5}},
\]

where \( R_1 \) is the radius of Saturn and \( \rho_1/\rho_2 \) is the ratio of densities in Saturn and the rings. Setting this ratio to unity yields a Roche limit that is about 2.5 times greater than the radius of Saturn - neatly coinciding with the outer limits of the rings.
For bodies of equal mass and density, the critical separation is not much greater than the radius of the primary or secondary body. In other words, two galaxies of nearly equal mass must get very close to one another before their tidal effects can significantly disrupt one another. Such close and consequential interactions were prevalent in the very early Universe, when the density of matter was much greater. We can estimate when this occurred by considering the current density of giant galaxies in the local Universe. The average separation between giant galaxies is roughly 1 Mpc, or about 50 times greater than their individual radii. Reduction of this separation to the Roche limit, or roughly 2.5x the respective radii, occurred when the scale of the Universe was some 20 times smaller. Therefore, the last epoch of dominant tidal disruption should have ended at a redshift of \( z \approx 20 \), and corresponding lookback time of roughly 13 Gyrs (see Endnote 28).

The foregone analysis ignores the glaring fact that galaxies are in motion. By considering the degree of motion (v), the volume density of galaxies (n), and the galaxy’s cross-sectional area (\( \sigma \)), we can derive the collisional timescale (\( \tau \)), whereby

\[
\tau = \frac{1}{(n\sigma v)}.
\]

By setting the collisional timescale to a cosmologically interesting 1 Gyr and the rms velocity equal to that seen in galaxy groups (about 150 km/s), we can solve for the density of galaxies necessary to achieve this frequency of collisions, ie.

\[
n = \frac{1}{(\tau \sigma v)}.
\]

For giant galaxies with cross-sectional areas corresponding to their Roche limits, the density amounts to roughly 5,000 galaxies per cubic Mpc. By contrast, groups in the local Universe have densities of \( n_0 \approx 1 \) giant galaxy/Mpc³. The higher density would have occurred when the relative scale of the Universe (\( R/R_0 \)) was

\[
\frac{R}{R_0} = \left( \frac{n_0}{n} \right)^{\frac{1}{3}},
\]

or about 1/15 the size it is today - again less than a billion or so years following the Big Bang. Since then, less disruptive interactions involving nearby dwarf galaxies have probably dominated the evolution of most giant galaxies.

These estimates notwithstanding, the actual rate of close interactions over cosmic time remains a hotly debated issue. Nearby examples of interacting galaxies, listed in Endnote 24 and discussed in Chapter 10, vividly demonstrate that close and tumultuous interactions have occurred up to the present day.

26. Galaxies with Active Nuclei

The nuclear activity in galaxies ranges from the mild LINERs in otherwise normal spiral galaxies, through the more powerful Seyfert and radio-lobe galaxies, to the most powerful quasars and blazars. The following 15 galaxies with active galactic nuclei (AGN) exemplify some of the variety found in the visible Universe ... out to a redshift of 5.5.
Table E9: Selected AGN Galaxies

*(in order of increasing distance)*

<table>
<thead>
<tr>
<th>Names(s) (1)</th>
<th>Type Comment (2)</th>
<th>RA (hr:min) Dec (°: ′) (3)</th>
<th>Size (′)  (m(B)) (mags) (4)</th>
<th>Redshift (\tau) (Gyr) (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3031 (M81)</td>
<td>Sb(r)I-II (LINER)</td>
<td>09:55:57 +69:04.1</td>
<td>26.9 x 14.1 7.9</td>
<td>0.0004 0.012</td>
</tr>
<tr>
<td>NGC 5128 (Centaurus A)</td>
<td>S0+S pec (radio-lobe)</td>
<td>13:25:48 -43:01.0</td>
<td>25.7 x 20.0 7.9</td>
<td>0.0008 0.015</td>
</tr>
<tr>
<td>NGC 4151</td>
<td>Sab(rs) (Seyfert 1)</td>
<td>12:10:54 +39:24.3</td>
<td>6.3 x 4.5 10-12</td>
<td>0.0033 0.045</td>
</tr>
<tr>
<td>NGC 4486 (M87/3C 274) (Virgo A)</td>
<td>E0 (radio-lobe) (optical-jet)</td>
<td>12:30:83 +12:23.6</td>
<td>8.3 x 6.6 9.6</td>
<td>0.0038 0.053</td>
</tr>
<tr>
<td>NGC 1068 (M77/3C 71)</td>
<td>Sab(rs)II (Seyfert 2)</td>
<td>02:42:68 -00:00.9</td>
<td>7x1 x 6.0 9.5</td>
<td>0.0041 0.054</td>
</tr>
<tr>
<td>NGC 4261 (3C 270)</td>
<td>E3 (radio-lobe)</td>
<td>12:19:39 +05:49.5</td>
<td>4.1 x 3.6 11.4</td>
<td>0.0069 0.091</td>
</tr>
<tr>
<td>NGC 7714 (Mrk 538)</td>
<td>SBb(s) pec (LINER)</td>
<td>23:36:23 +02:09.3</td>
<td>1.9 x 1.4 13.0</td>
<td>0.0100 0.13</td>
</tr>
<tr>
<td>NGC 1275 (3C 84) (Perseus A)</td>
<td>E pec (Seyfert 2)</td>
<td>03:19:80 +41:30.7</td>
<td>2.2 x 1.7 11-13</td>
<td>0.0181 0.24</td>
</tr>
<tr>
<td>NGC 1265 (3C 83.1)</td>
<td>E (radio-lobe)</td>
<td>03:18:26 +41:51.5</td>
<td>1.8 x 1.6 13.2</td>
<td>0.0258 0.34</td>
</tr>
<tr>
<td>Cygnus A (3C 405)</td>
<td>Interacting (radio-lobe)</td>
<td>19:59:47 +40:44.0</td>
<td>&lt;0.1</td>
<td>0.0569 0.74</td>
</tr>
<tr>
<td>BL Lacertae</td>
<td>Blazar</td>
<td>22:02:72 +42:16.7</td>
<td>&lt;0.1 14-17</td>
<td>0.0695 0.91</td>
</tr>
<tr>
<td>3C 273</td>
<td>Quasar (radio-lobe) (optical-jet)</td>
<td>12:29:11 +02:03.1</td>
<td>&lt;0.1 12-13</td>
<td>0.1583 1.8</td>
</tr>
<tr>
<td>OJ 287</td>
<td>Blazar</td>
<td>08:54:81 +20:06.5</td>
<td>&lt;0.1 12-16</td>
<td>0.3060 3.1</td>
</tr>
<tr>
<td>3C 48</td>
<td>Quasar</td>
<td>01:37:69 +33:09.6</td>
<td>&lt;0.1 16-17</td>
<td>0.3670 3.5</td>
</tr>
</tbody>
</table>
Notes to table:

(1) **Name(s)** of galaxy in the New General Catalogue (NGC), Messier (M), Third Cambridge Catalogue of Radio Sources (3C), and other listings.

(2) **Galaxy classification**, based mostly on the Hubble-Sandage system. **Proper names and other comments** ... (LINER) refers to a low-ionization nuclear emission region.

(3) **Right Ascension** (celestial longitude) in units of hours (hrs) and minutes (min), and **Declination** (celestial latitude) in units of degrees (°) and arcminutes (′), both coordinates precessed to the 2000.0 epoch.

(4) **Angular dimensions** along the major axis (2a) and minor axis (2b), in arcminutes (′).

**Apparent magnitude** at B-band, before correction for foreground extinction by dust. Magnitude ranges are listed for highly variable galaxies.

(5) **Cosmological Redshift** (z), where \( z = \Delta \lambda / \lambda \), after correction for Doppler shifts due to motions of the Sun and Galaxy with respect to the centroid of the Local Group.

**Lookback time** (\( \tau \)) in giga-years (Gyrs) and corresponding distance (in light-Gyrs), based mostly on the cosmological redshift (z) of the galaxy or associated galaxy group and the assumption of free expansion, where \( \tau = \tau_o \left\{ 1 - \left( \frac{1}{1 + z} \right) \right\} \) and where the Hubble time \( \tau_o = 1/H_o = 13.1 \) Gyrs, assuming \( H_o = 75 \) km/s/Mpc.

References for table:


### 27. Galactic Black Holes

Like their stellar counterparts, galactic black holes are thought to occur whenever a concentration of gravitating matter imposes escape velocities that exceed light speed. Within the so-called **event horizon** of the black hole, no form of matter or radiation can escape the inexorable grip of the black hole’s gravitation. The fabric of space and arrow of time are warped beyond recognition within the event horizon, leaving us to theorize about the nature of this abyss.

The primary difference between galactic and stellar black holes is that the mass of a galactic black hole is so much greater. Instead of a few solar masses, galactic black holes weigh in at several million to several billion solar masses. Therefore, galactic black holes cannot be the collapsed cores of single massive stars, but must involve a tremendous concentration of stars - or of their shredded remains.

**Black Hole Basics:**

One can quantify the masses and sizes of galactic black holes by equating the gravitational and kinetic energies, as would be the case at the brink of escape.
where \( v_{\text{esc}} \) is the escape velocity. Solving for the radius \( R \) yields

\[
\frac{GM}{R} = \frac{mv_{\text{esc}}^2}{2},
\]

and setting the escape velocity equal to that of light \( (v_{\text{esc}} = c) \) produces the relation

\[
R_S = \frac{2GM}{c^2},
\]

where \( R_S \) is the Schwarzschild radius (named after the German astrophysicist Karl Schwarzschild, who worked out this solution shortly after Albert Einstein published his general theory of relativity). This radius defines the size of the event horizon for a non-rotating spherical black hole. Modifications of this solution have been found for rotating black holes and for non-spherical shapes. Assuming the simple Schwarzschild solution, however, provides reasonable estimates for the sizes and densities of black holes of differing mass - as itemized in the following table.

### Table E10: Black Hole Dimensions

*(In order of increasing black hole mass)*

<table>
<thead>
<tr>
<th>Candidate Name(s)</th>
<th>Type</th>
<th>Mass (M/M[Sun])</th>
<th>Schwarzschild Radius</th>
<th>Avg. Density (grams/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cygnus X-1 (HDE226868)</td>
<td>Stellar BH</td>
<td>10.0 ± 5.0</td>
<td>30 km 1.0 x 10⁻⁴ ls</td>
<td>1.6 x 10¹⁴</td>
</tr>
<tr>
<td>LMC X-1 (0540-697)</td>
<td>Stellar BH</td>
<td>7.0 ± 3.0</td>
<td>21 km 7.0 x 10⁻⁵ ls</td>
<td>3.7 x 10¹⁴</td>
</tr>
<tr>
<td>LMC X-3 (0538-641)</td>
<td>Stellar BH</td>
<td>10.5 ± 3.5</td>
<td>31 km 1.0 x 10⁻⁴ ls</td>
<td>1.6 x 10¹⁴</td>
</tr>
<tr>
<td>M82 (NGC 3034)</td>
<td>Amorphous Gal (Starburst Nuc)</td>
<td>&gt;500</td>
<td>&gt;1.5 x 10⁷ km 4.9 x 10⁻³ ls</td>
<td>7.3 x 10¹⁰</td>
</tr>
<tr>
<td>Milky Way (Sgr A*)</td>
<td>SBbc(rs)I-II</td>
<td>2.6 x 10⁶</td>
<td>7.7 x 10⁶ km 26 ls</td>
<td>2.7 x 10³</td>
</tr>
<tr>
<td>M32 (NGC 221)</td>
<td>E2</td>
<td>3 x 10⁶</td>
<td>8.9 x 10⁶ km 30 ls</td>
<td>2.0 x 10³</td>
</tr>
<tr>
<td>M77 (NGC 1068)</td>
<td>Sb(rs)II (AGN)</td>
<td>1 x 10⁷</td>
<td>3.0 x 10⁷ km 99 ls = 1.6 lm</td>
<td>180</td>
</tr>
<tr>
<td>M31 (NGC 224)</td>
<td>SbI-II</td>
<td>3 x 10⁷</td>
<td>8.9 x 10⁷ km 300 ls = 5 lm</td>
<td>20</td>
</tr>
<tr>
<td>M105</td>
<td>E0</td>
<td>1 x 10⁸</td>
<td>3.0 x 10⁸ km</td>
<td>1.8</td>
</tr>
<tr>
<td>(NGC 3379)</td>
<td>M84 (NGC 4374)</td>
<td>E1 (radio jet)</td>
<td>$1 \times 10^9$</td>
<td>$3 \times 10^9$ km</td>
</tr>
<tr>
<td>-----------</td>
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<td>----------------</td>
</tr>
<tr>
<td>M87 (NGC 4486)</td>
<td>E0 (radio-opt jet)</td>
<td>$3 \times 10^9$</td>
<td>$8.9 \times 10^9$ km</td>
<td>$8.2$ lh</td>
</tr>
</tbody>
</table>

References for table:

With the exception of M82, the masses in the above table are determined from dynamical considerations of the observed velocities of stars and gas close to the center of mass (see Endnote 16). The mass of M82 is based on the period and amplitude of X-ray flickering.

The abbreviations “ls”, “lm”, and “lh” respectively refer to light-second, light-minute, and light-hour.

The above table underscores the tremendous differences between stellar and galactic black holes. As the masses of the respective black holes vault from several Suns to millions and billions of Suns, the Schwarzschild radii proportionately increase from several km to millions and billions of km. The corresponding light-crossing times increase from microseconds to hours, placing constraints on the flickering timescales of any emission produced by infalling material near the event horizons.

For stellar black holes, the average densities inside the event horizons are of nuclear magnitude. The galactic black holes are much roomier, hosting average densities ranging from that of the solar core (~100 grams/cm$^3$), to that of water or the whole Sun (~1 grams/cm$^3$), to that of air (~$10^{-3}$ grams/cm$^3$). The actual nature of the matter that is concentrated inside these netherworlds is beyond our empirical knowing.

The estimated masses of the galactic black holes trend with the masses of the host bulges - the black holes amounting to 0.5 to 1.0 percent of the spheroidal components. This correlation indicates a generic relation between black holes and massive bulges. It also indicates that the quasar activity observed at high redshift - if due to accreting galactic black holes - was most likely the result of massive bulges having been built shortly after the Big Bang.

**Black Hole Energetics**

To get power from a black hole, the “central engine” must be fueled. Astronomers envision that galaxy mergers and other less drastic interactions between galaxies can send gas, stars, and stellar remnants plummeting into a galaxy’s nucleus and whatever black
hole may lurk there. As matter hurtles toward the black hole’s event horizon, the conversion of gravitational potential energy into kinetic energy provides a vast supply of mechanical power. This can be formulated by considering the gravitational potential energy released when a test particle falls from infinite radius to somewhere near the Schwarzschild radius of the black hole

$$G.E. = \frac{G M m}{R_s},$$

where M is the mass of the black hole, and m is the test particle’s mass. The corresponding power is obtained by taking the time derivative such that

$$\text{Power} = \frac{d(G.E.)}{dt} = \left(\frac{GM}{R_s}\right)\left(\frac{dm}{dt}\right),$$

where dm/dt is the mass inflow rate. For example, a billion solar-mass black hole hosting a mass inflow rate of 1 M[Sun]/yr could generate up to 7 trillion solar luminosities worth of mechanical power.

Once the material crashes onto the accretion disk, the kinetic energy is then thermalized and re-released in the form of X-rays and outflowing jets of magnetized plasma. The efficiency of this conversion determines the actual radiative and mechanical luminosities that are observed, e.g.

$$L_{\text{rad}} = \text{eff} \text{ Power},$$

where the radiative efficiency (eff) is thought to be somewhere between 1 and 10 percent. Given such high efficiencies, the most luminous quasar activity can be explained as arising from the accretion of matter near a supermassive black hole.

An accreting black hole’s radiative luminosity is ultimately limited by the radiation pressure which this same luminosity engenders on the black hole’s accreting environment. Once the radiation pressure exceeds the gravitational binding, the influx of “fuel” is squelched until the pressure is again below the limit. The equality between radiation pressure force and gravitational force can be formulated as

$$\frac{\sigma L_{\text{rad}}}{4 \pi R^2 c} = \frac{G M m_H}{R^2},$$

where M is the mass of the black hole, m_H is the mass of the dominant hydrogen nucleus, and the electron-photon cross section ($\sigma = 6.65 \times 10^{-25}$ cm$^2$) can be regarded as the relevant efficiency for the radiation pressure term. Solving for the luminosity yields

$$L_{\text{rad}} = \frac{4 \pi G M m_e}{\sigma},$$

or

$$\frac{L_{\text{rad}}}{L_\odot} = 3.3 \times 10^4 \frac{M}{M_\odot}.$$  

This threshold state is known as the Eddington Limit and is thought to apply to feeding AGNs, providing yet another method of “weighing” the putative black holes within.

For example, the highest luminosities observed in quasars ($L \equiv 10^{13} L_\odot$) would require something like a billion solar-mass black hole emitting at the Eddington Limit.

The corresponding mass inflow rate would be something like 100 Suns/yr, assuming an energy conversion efficiency of 1%.