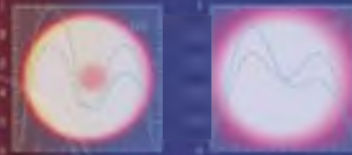


v (km s^{-1})

Supermassive Black Holes in the Universe

$$= 1.6 \times 10^8 \text{K} \left(\frac{m}{M_{\odot}} \right)^{-1} \times \left(\frac{M_{\text{BH}}}{10^8 M_{\odot}} \right)^{-1/2} \quad (5)$$



σ (km s⁻¹)

INAUGURALE REDE door Prof. Dr. Heino Falcke

SUPERMASSIVE BLACK HOLES IN THE UNIVERSE

This whole way of thinking and acting rests on the assumption that reality is reliable, not that disasters, and failures, and evil things will never happen, but that the world in which they happen ultimately makes sense. It is not just 'buzzing, booming confusion' but springs from the will of a creator whose purposes are trustworthy and whose ultimate aim is glorious however dark and mysterious the way to it.

(John Habgod in "Can Scientists Believe?", Ed. Sir Nevill Mott, 1991)

1. Introduction

In the early sixties, a number of strong radio sources were detected that were associated with optical point sources. Although they appeared stellar on photographic plates, they had very strange optical emission lines which were different from anything seen before in stars. Schmidt (1963) realized for one of this “quasi stellar radio sources” (henceforth quasars), 3C 273, that the emission lines could be explained with hydrogen emission at a redshift of $z = 0.158$. Soon very similar objects were found.

This unusual high – at least in those days – redshift lead to another problem. The optical brightness of $m_B = 13.1$ corresponded to a luminosity of $L = 2 \times 10^{46} \text{ erg s}^{-1}$ or $0.5 \times 10^{13} L_\odot$ ($L_\odot =$ solar luminosity). Since the sources showed variability on timescales of less than a year, the size of the emitting region was restricted to be smaller than one light year. Although confined into a 10^{-12} th fraction of the volume of a galaxy, the luminosities of these quasars exceeded the luminosity of an entire galaxy. It turned out that the most efficient way to release this amount of energy is accretion in a deep, i.e. relativistic, gravitational potential. Supermassive black holes with masses million and even billion times that of the sun emerged as the major paradigm to explain the huge energy output of the central engine of active galactic nuclei (AGN). In the following I will describe some of the basic ideas and observational findings that have lead to the present day picture about these black holes. This write-up is a significantly expanded version of a lecture I first wrote up together with my student Andreas Brunthaler for an European VLBI Network (EVN) Summer School near Bologna in 2001.

2. Black Holes – Basic Principles and Numbers

A key feature of general relativity is that the presence of mass distorts space-time. In a black hole the spacetime is curved to such an extent that light can no longer escape. The characteristic size of a black hole is given by its Schwarzschild radius R_S .

This radius has a special meaning in the so called Schwarzschild metric in General Relativity, but in classical terms could be understood simply as the radius at which the escape velocity v_{esc} of a body is equal to the speed of light c :

$$v_{esc} = \sqrt{\frac{2GM}{R}} = c \Rightarrow R_S = \frac{2GM_{BH}}{c^2} = 3 \text{ km} \times \frac{M_{BH}}{M_\odot}. \quad (1)$$

Here G is the Gravitational constant, M_{BH} is the black hole mass, and M_\odot is a solar mass.

The escape speed is the speed a particle needs to achieve at the surface of a massive body to escape its gravitational grip (or the speed a rocket needs to be launched with to leave the earth). Photons – that make up our visible light for example – are the fastest entities in this universe and obviously they propagate with the speed of light. No information can be transmitted faster than this. Hence, if the escape speed of a mass concentration exceeds even the speed of photons, nothing in the known universe could possibly escape such an object. Any material or radiation – also light, electric current, or radio waves – that fall towards such a massive object and cross this boundary at one Schwarzschild radius will be trapped forever. The invisible membrane of “no return” around the mass is called the event horizon and the object itself is called a black hole.

Alternatively one can also state that everything that falls onto a black hole reaches a velocity close to the speed of light near the event horizon. This makes black holes by definition the deepest gravitational wells in the universe. Just like a brick that falls from the top of a tall skyscraper is much more damaging to an unsuspecting pedestrian than a brick falling from the first floor, any material falling into a black hole assumes enormous amounts of energy.

However, even before a particle or a photon has reached the event horizon, it already experiences a world of gravity very different from everything we know. Since a heavy mass curves spacetime a light ray will not propagate on a straight line but on curved paths. In fact, for certain configurations a light ray could rotate indefinitely around a black hole. The bending of rays will also distort images and allows one to look “around the corner” – a person with a black hole in his head should be able to see his neck without a mirror. Photons that are emitted close to but outside the event horizon and have to fight against the gravitational potential, will also suffer almost catastrophic energy losses as they try to escape to infinity. Energy loss for a photon ($E_\nu = h\nu$; E_ν =photon energy, h =Planck constant, ν =frequency) is reflected in a decrease in its frequency. This is called redshift as photons will change color: from green to red. Indeed, in an extreme case, a proud and brilliant photon of visible blue light emitted near the event horizon might escape only as a feeble FM-band radio photon to an observer on earth.

2.1. ACCRETION

In an astrophysical context these properties of black holes are highly welcome. The huge energy gain matter achieves while falling toward a black hole can be used for heating and radiation of that very matter, thus making visible what that is inherently invisible – the vicinity of a black hole.

In a galaxy the strong gravity field of the black hole will attract gas clouds in the central region of its host galaxy. This gas clouds will collide with each other in the vicinity of the black hole and transform kinetic energy into “frictional” heating. Usually the gas clouds will have a certain amount of angular momentum which has to be conserved. This will lead to the formation of an accretion disk. The particles in the disk will continue to interact with each other and heat the disk even more. In this process the particles will lose kinetic energy and move inwards while angular momentum is transported outwards, until the gas finally reaches the last stable orbit and falls into the black hole. The heated accretion disk will radiate predominantly in the optical, UV, and soft X-rays and produce the enormous luminosities observed in quasars.

The energy output is related to the rate of accreted material. A particle with mass m which falls in a gravitational potential of a central mass M from an infinite distance to a distance R from the black hole gains the energy:

$$U = \frac{GMm}{R}. \quad (2)$$

In the case of a black hole, the accreted material can only radiate until it reaches the event horizon R_S . If the energy is converted with an efficiency of η into radiation, the luminosity depends on the accretion rate \dot{m} as:

$$L = \eta \dot{U} = \eta \frac{GM_{BH}}{R_S} \frac{dm}{dt} = \eta \frac{1}{2} \dot{m} c^2 \quad (3)$$

or

$$L = 10^{46} \frac{\text{erg}}{\text{s}} \left(\frac{\eta}{0.1} \right) \left(\frac{\dot{m}}{\text{M}_{\odot} \text{yr}^{-1}} \right). \quad (4)$$

For a fast rotating black hole the efficiency of energy production can be as high as 40% – this means that almost half of the entire rest mass energy mc^2 is converted into heat and radiation. To get a feeling for the efficiency one can mention that the rest mass energy of just one liter of water would be enough to sustain the primary energy consumption of the Netherlands for an entire week¹.

Most of the luminosity of an accretion disk will be radiated in the inner $10 R_S$, hence over an area $A = \pi(10R_S)^2$. If we assume the emission is black body radiation, we can use the Stefan-Boltzmann law

$$\sigma T^4 = \frac{L}{A} \Rightarrow T = \left(\frac{L}{A\sigma} \right)^{\frac{1}{4}} = 1.6 \times 10^5 \text{K} \left(\frac{\dot{m}}{\text{M}_{\odot} \text{yr}^{-1}} \right)^{\frac{1}{4}} \times \left(\frac{M_{BH}}{10^8 \text{M}_{\odot}} \right)^{-\frac{1}{2}} \quad (5)$$

¹The primary energy consumption of the Netherlands was 3.91 Quadrillion Btu = 4×10^{18} Joule in 2000 according to a study of the US Energy Information Administration of the DOE (<http://www.eia.doe.gov/emeu/international/total.html>).

where σ is the Stefan-Boltzmann constant to estimate a temperature. With a temperature exceeding 10^5K , the central engine is naturally expected to radiate mainly in the ultraviolet. Indeed, quasars were found to have their main energy output in this wavelength range.

Hence, a quasar with a luminosity of 10^{46} erg s^{-1} and an efficiency of $\eta = 0.1$ would accrete one solar mass per year. This corresponds to the consumption of 40 times the total water content of the entire earth per second². I leave it to the imagination of the reader to calculate for how long one second of AGN fuel would solve the energy problems of The Netherlands.

If there is $\sim 10^{10}M_{\odot}$ of material in the central region of the galaxy, the lifetime of the quasar would be limited to a few times 10^9 years. Hence, the quasar phase can be just a short fraction of the lifetime of a galaxy and other estimates suggested that the quasar lifetime typically is even shorter, about 10^8 years.

2.2. THE EDDINGTON LIMIT - ESTIMATING A MASS

As we have seen, the central engine is generating a very large amount of radiation in order to sustain its huge luminosity output. This radiation, however, also exerts a force on the accreting material and sets in turn an upper limit on the luminosity. Beyond this limit the radiation from the accretion process would blow away the very matter that provides the fuel for the luminosity output.

One can calculate this effect rather simply. The so called ‘‘Eddington limit’’ is reached if the radiation force is equal to the gravitational force.

$$\frac{\sigma_{th}L}{4\pi R^2c} < \frac{GM_{BH}m_p}{R^2}. \quad (6)$$

The radiation interacts mainly with the electrons, while the gravitation affects predominantly the heavy protons but both are strongly coupled through the Coulomb force. σ_{th} is the Thomson cross section for electron photon scattering, L the luminosity, and m_p the proton mass. One can use this requirement to obtain a *lower limit* of the black hole mass for a given luminosity assuming isotropic emission:

$$M_{BH} > 0.8 \times 10^8 M_{\odot} \left(\frac{L}{10^{46} \text{ erg s}^{-1}} \right). \quad (7)$$

²There are about 1.4 Billion cubic kilometer of water in Oceans, Seas, & Bays. Source: Gleick, P. H., 1996: Water resources. In Encyclopedia of Climate and Weather, ed. by S. H. Schneider, Oxford University Press, New York, vol. 2, pp.817-823.

We can conclude that, in order for a luminous quasars to function through accretion, it indeed requires at least a mass of about $10^8 M_\odot$ in its center to counteract its own radiation pressure.

To get a feeling for the configuration, one can calculate an equivalent mass density of a black hole of that mass. We define the *equivalent* mass density as the critical density of a speculative object with a homogeneous mass distribution of a given mass that is needed to turn it into a black hole.

The characteristic size of a black hole is set by the Schwarzschild radius; the volume is $V = 4/3 \times \pi R_S^3$. Accordingly, the equivalent mass density will be

$$\rho_{BH} = \frac{M_{BH}}{4/3\pi(R_S)^3} = 1.8 \frac{\text{g}}{\text{cm}^3} \left(\frac{M_{BH}}{10^8 M_\odot} \right). \quad (8)$$

On an astrophysical scale, this density is not that much different from that of water (1 g/cm^3). The Schwarzschild radius for a $10^8 M_\odot$ black hole is roughly one astronomical unit ($1 \text{ AU} = 1.5 \times 10^{13} \text{ cm}$ is the distance between earth and sun.)

Hence, the volume inside the Earth orbit filled with water would immediately become a black hole. For that reason I always advise my students to make sure their water faucets at home are closed when they leave for an extended vacation – we do not want to take any risks!

3. Observational Evidence

The theoretical estimates made in the first section are essentially what made the black hole story such an success in the first place, because they rely on a very few and basic physical estimates. It is surprising how well these estimates reproduce the fundamental properties of quasars (and, by the way, also of stellar mass black holes). However, the fact that accretion onto a black hole can explain the observed luminosities, is no sufficient proof for the existence of black holes – is there anything else?

Indeed, black holes were used to explain the luminous emission of quasars, however, many studies have now shown that indeed quasars are the nuclei of distant galaxies. Of course, the more distant an object the earlier the epoch of the universe it is being observed in. If black holes were “alive and kicking” in the early phase of the universe, and their mass should still be found at the present day in the hearts of normal galaxies. The only process we now that can reduce a black hole mass, Hawking radiation, is not efficient to evaporate massive black holes on time scales of the age of the present day universe.

Moreover, since the quasar-phase is just a short fraction of the lifetime of a galaxy, one requires a rather large fraction of galaxies to have been

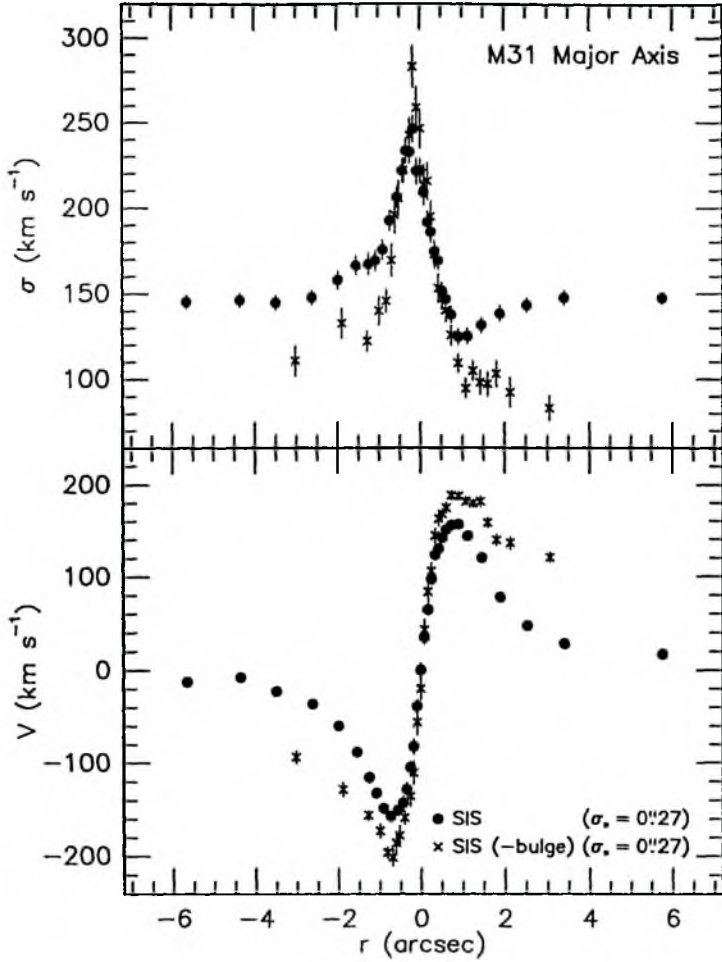


Figure 1. Velocity $V(r)$ (bottom) and velocity dispersion $\sigma(r)$ (top) profiles along the nucleus major axis of M31. (Taken from Kormendy and Richstone 1995).

a quasar or AGN at some point during their evolution. This leads to the immediate prediction of massive black holes at the center of many, perhaps all, galaxies – even those who do not show prominent signatures of “nuclear activity”. To find stronger evidence for supermassive black holes, one therefore has to search for dynamical evidence of them in *dead quasars*. This can be done easiest in normal nearby galaxies and we discuss a few

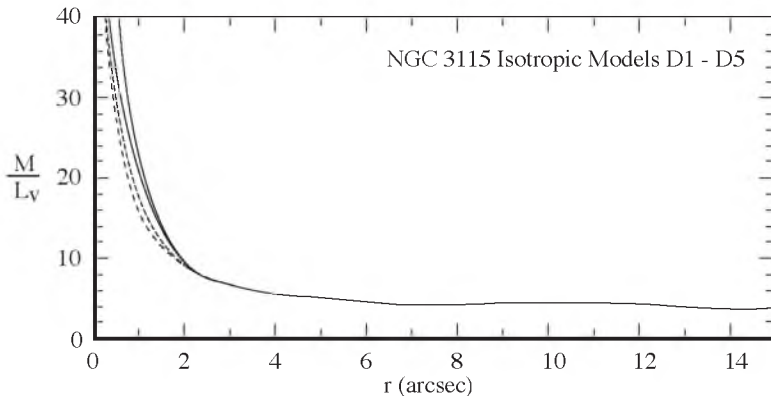


Figure 2. Mass-to-light ratio interior to radius r for NGC 3115. M/L_V increases at $r < 2''$ by a factor of ~ 10 indicating the presence of a massive dark object. (Taken from Kormendy and Richstone 1995).

such studies in the following. The exceptional case of the black hole in the center of the Milky Way will be discussed in a separate chapter.

3.1. STELLAR VELOCITY DISPERSION

The main idea for measuring masses uses Kepler’s and Newton’s laws, which were first derived for the solar system. The speed of a planet around the sun, or of any small mass orbiting around a central, much larger “point” mass, is proportional to the square root of the central mass divided by the square root of the distance between the two masses. Thus, one only needs to measure a velocity and a distance of small orbiting objects.

A common way of measuring velocities is through spectroscopic observations of emission and absorption lines and observe the velocity-dependent Doppler shift of the line frequency.

Roughly speaking, in the centers of galaxies stars revolving around the nucleus will exhibit absorption lines, while hot ionized gas will produce emission line that can both be measured. Long-slit spectroscopy of stellar absorption lines in nearby galactic nuclei indeed shows high rotational velocities and a high velocity dispersion towards the center. The velocities are measured from the Doppler shift of the line centroids, reflecting ordered motion in a disk of stars, while the velocity dispersion is inferred from the line width, produced by an ensemble of randomly orbiting stars.

For an isotropic velocity field with net rotation v and velocity dispersion

σ we can derive a central mass of

$$M(r) = \frac{Rv^2}{G} + \frac{R\sigma^2}{G} \quad (9)$$

using essentially the Kepler law and assuming that the stars are virialized.

Figure 1 shows the velocity and velocity dispersion profiles along the nucleus major axis of M31. The velocity dispersion increases towards the center of M31 to $\sim 250 \text{ km s}^{-1}$ while the velocities increase to $\sim 200 \text{ km s}^{-1}$ before they drop to 0 km s^{-1} in the center due to the finite slit width over the nucleus. Kormendy (1988) derived a dark object mass of $\sim 10^7 M_\odot$ for this galaxy.

Using formula 9, one can calculate the mass inside a given radius and compare it with the measured stellar light. Figure 2 shows the mass-to-light ratio M/L_V for the galaxy NGC 3115 derived in this way. It stays roughly constant in the outer parts and increases drastically towards the central region of the galaxy. The kinematic data indicates that NGC 3115 harbors a massive dark object with a mass of $10^9 M_\odot$ (Kormendy and Richstone, 1992) in its center.

3.2. HIGH-RESOLUTION SPECTROSCOPY OF GAS

A further hint for massive matter concentrations comes from the kinematic behavior of the interstellar gas close to the core of galaxies. The Hubble Space Telescope (HST) is able to resolve the dynamics of stars and the gas in nearby galaxies. A prime example is the nearby giant elliptical galaxy M87 which contains a hot rotating disk in the center (see Figure 3). Measurements of the radial velocities using spectroscopy of emission lines from the ionized gas show the gas to be in Keplerian rotation about a mass of $M = 2.4 \times 10^9 M_\odot$ within the inner 18 pc of the nucleus (Ford *et al.* 1994; Harms *et al.* 1994).

3.3. REVERBERATION MAPPING

A rather clever method for determining black hole masses was used by Peterson & Wandel (2000) to get similar estimates for more distant, active objects.

Optical spectroscopy of quasars usually shows a series of broad emission lines which are assumed to come from gas orbiting the black hole. The width of the line is again given by the Doppler effect. The gas is excited by the bright emission of the quasar seen in the ultraviolet (UV). Those lines are much too close to the black hole as to be resolved by any optical telescope. To nevertheless get an estimate for the distance of the lines from the nucleus, one can wait for changes in the intensity of the quasar continuum

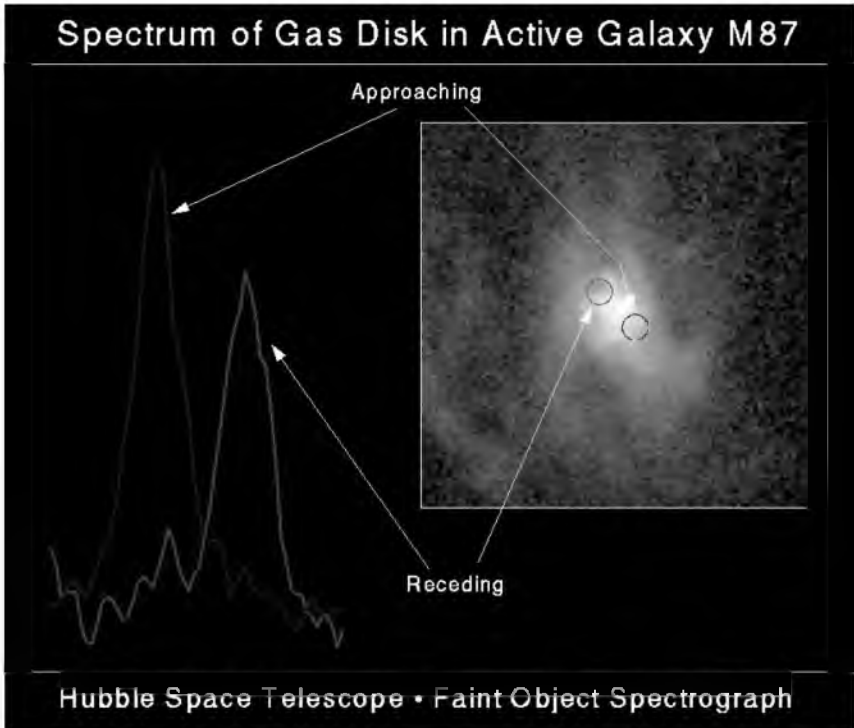


Figure 3. Hubble Space Telescope image of a rotating disk in M87. The emission lines of the receding part are redshifting, while the lines of the approaching part are blue-shifted with respect to the systematic velocity of the galaxy, yielding evidence for a massive dark object – presumably a black hole. (Ford *et al.* 1994)

emission. Since the emission lines are further away from the nucleus, the lines will react to the increased UV radiation with a certain time delay due to the finite speed of light. Measuring this delay then gives one the desired distance. However, this is a tedious exercise, as one has to observe a single galaxy almost every day for an extended period of time. Such observations are made in large collaborations with fancy names such as “Lovers of Active Galaxies – LAG”.

By now a reasonably large set of such observations have been made. If one plots the width (representing the velocity) of individual emission lines in the spectrum against their time lag (representing a distance), one can fit the data by a straight line in a logarithmic plot. According to Kepler’s law one can then get the mass of the central object from the interception of the

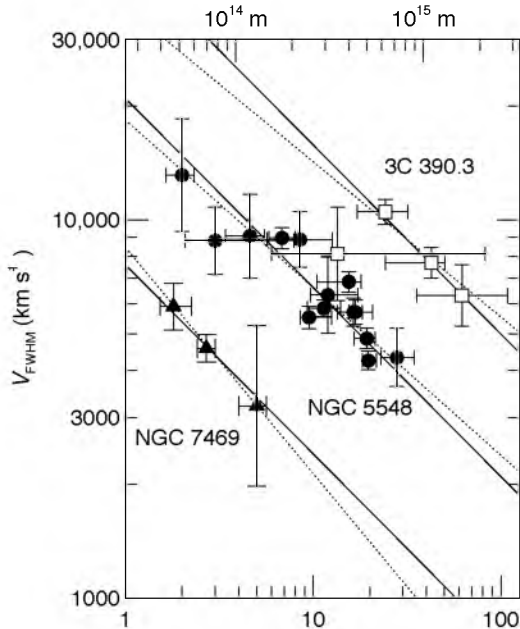


Figure 4. Width of different emission lines in three different active galaxies versus the measured time lags of the line with respect to the continuum. The solid lines show the $1/\sqrt{\tau}$ dependence expected for a Keplerian velocity distribution expected for a gravitational potential dominated by a black hole. The interception with the y-axis is proportional to the black hole mass and ranges from $6 \times 10^7 M_{\odot}$ to $3 \times 10^8 M_{\odot}$ (from Peterson & Wandel 2000).

fitted line with the y-axis. All data are nicely consistent with a gravitational potential dominated by a point mass of several million solar masses (Figure 4).

3.4. WATER MASERS – NGC 4258

Strong evidence for a supermassive black hole comes also from interferometric spectral line observations of water vapor maser emission in the centers of galaxies. Radio astronomical interferometry is the only tool that allows one to actually resolve emission lines within a few light years of the black hole.

The spectrum of the H_2O maser emission in the Seyfert galaxy NGC 4258 consists of maser components at the systematic velocity of the galaxy as well as high-velocity masers which are Doppler shifted by $\pm 1000 \text{ km s}^{-1}$.

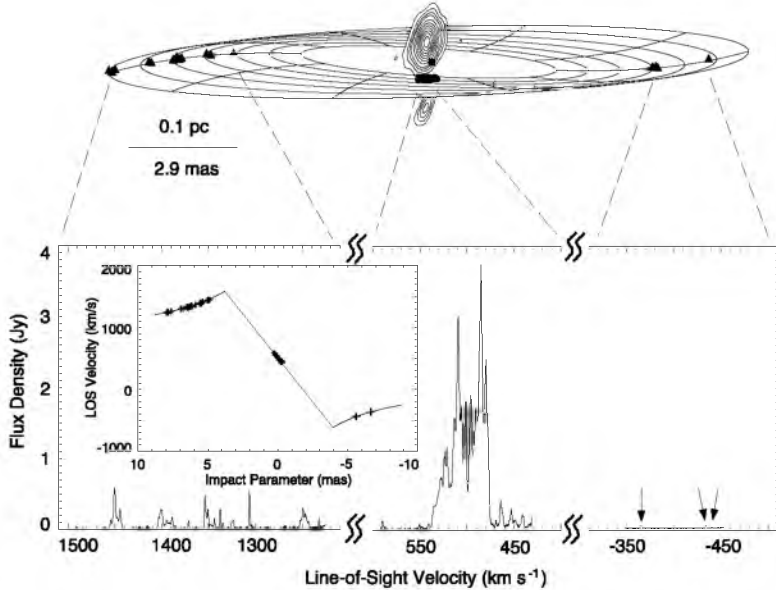


Figure 5. The warped disk model, the maser positions and the 22 GHz continuum emission of a sub-parsec-scale jet from VLBI observations of NGC 4258 (top). Also shown is the total spectrum with masers at the systematic velocity of $\sim 470 \text{ km s}^{-1}$ and the *high-velocity* masers Doppler shifted by $\pm 1000 \text{ km s}^{-1}$. The inlay shows the line-of-sight velocity versus the the impact parameter for a Keplerian disk with the maser data superposed. (Taken from Herrnstein *et al.* 1999).

High resolution Very Long Baseline Interferometry (VLBI) observations show the maser spots in a thin warped disk around the center. The masers with the systematic velocity appear in front of the nucleus, while the blue- and red-shifted components are on the approaching and receding sides of the disk which is in almost perfect Keplerian rotation (Figure 5). From the rotation and the distance of the source, one can estimate an enclosed mass of $3.6 \times 10^7 M_{\odot}$ within 0.1 parsecs (Miyoshi *et al.* 1995; Herrnstein *et al.* 1997).

3.5. RELATIVISTICALLY BROADENED IRON $K\alpha$ -LINE

X-ray spectroscopy of Seyfert galaxies have revealed enormously broadened iron $K\alpha$ emission lines with line widths of $\sim 100,000 \text{ km s}^{-1}$. The huge line width seems to require significant Doppler broadening due to material orbiting with speeds close to the speed of light, just what one suspects for accretion disks around black holes. ASCA (Advanced Satellite for Cosmology and Astrophysics) observations by Tanaka *et al.* (1995) found that the

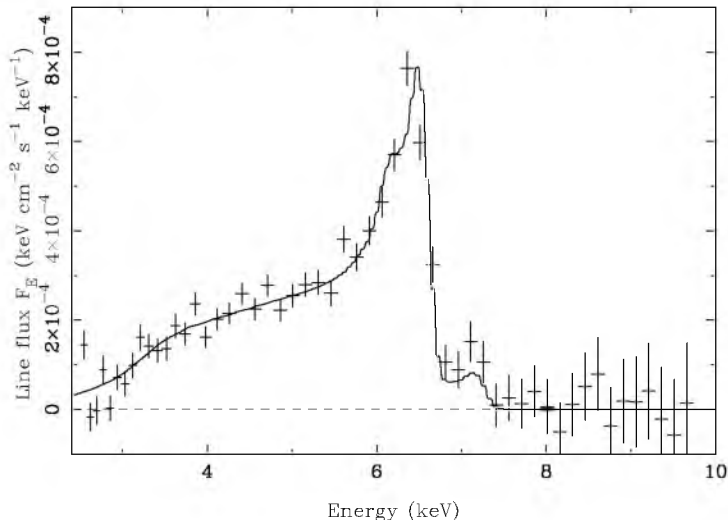


Figure 6. Continuum subtracted relativistic iron line profile from an XMM-Newton observation of MCG-6-30-15 (Taken from Fabian *et al.* 2002). The broad wing of the line probably indicates relativistic broadening in the gravitational potential of a black hole due to orbital velocities close to the speed of light.

iron line profile in MCG-6-30-15 could indeed be explained this way. Recent XMM-Newton observations (see Figure 6) find also extremely broad and redshifted emission indicating an origin in the central regions of an accretion disk around a rotating black hole (Wilms *et al.* 2002; Fabian *et al.* 2002).

3.6. BLACK HOLES AND THEIR HOST GALAXIES

From many such studies we now have a rather comprehensive view of the demography of black holes. Statistically one can infer from this that essentially every galaxies has a massive dark object in its center. This allows one to raise the question whether and how the evolution of black holes and galaxies are connected. It is therefore important to search for correlations between properties of the black hole and those of galaxies. Already Kormendy & Richstone (1995) suggested from their data that the mass of black holes could be related to the mass of the host galaxy. This suggestion was significantly strengthened when Gebhardt *et al.* (2000) and Ferrarese and Merritt (2000) found a strong correlation between the black hole mass and the velocity dispersion of stars in the bulge of the host galaxy. The bulge is the spheroidal stellar component of a galaxy. Figure 7 shows this

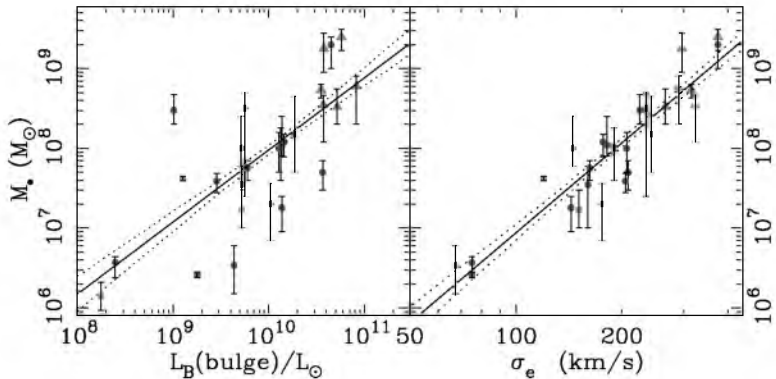


Figure 7. Black hole mass versus bulge luminosity (left) and the velocity dispersion (right). The velocity dispersion shows a tight correlation with the the mass of the central black hole. Solid and dotted lines are the best fit and their 68% confidence bands. (Taken from Gebhardt et al. 2000).

correlation for 26 galaxies with black hole masses from kinematics of stars, gas and masers.

The velocity dispersion of stars in the bulge depends on the mass of the spheroidal stellar component and this correlation indicates that the more massive the bulge the heavier is the black hole. This suggests that indeed the evolution of black holes and their host galaxies are intimately linked.

There are various processes for bulge and black hole mass evolution: A primordial hydrogen cloud collapses around a small black hole. Infalling gas feeds the black hole and forms stars. Finally the collapse yields a giant elliptical galaxy or bulge and the black hole growth stops. Another scenario is the merger of two spiral galaxies with black holes. The galaxies collide and the merger yields an elliptical galaxy with a larger central black hole. The central black hole could also grow throughout the cosmological history by accretion of ordinary or dark matter through the galactic disk or halo into the center. Hence, while black holes can grow in different ways, the reason why black holes and bulges are so intimately linked remains a big puzzle.

4. The Dark Mass in the Galactic Center

The closest place, however, to look for a supermassive black hole is the center of our own Galaxy.

The compact radio source Sagittarius A* (Sgr A*) in our Galactic Center is thought to contain a black hole. The radio source has many properties very similar to those associated with other suspected black hole candidates

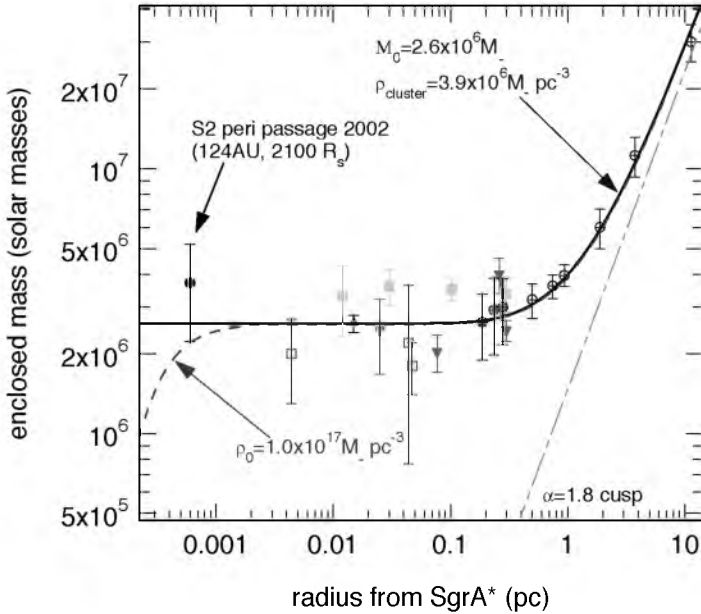


Figure 8. Enclosed mass as a function of radius from Sgr A* in the Galactic Center (Taken from Schödel *et al.* 2002).

(Falcke & Biermann 1999). For a detailed review about the inner parsecs of our Galaxy see Melia and Falcke (2001).

Measurements of stellar proper motions in the vicinity of Sgr A* have revealed a dark mass in the Galactic Center. The center of gravity coincides with Sgr A* within 0.01 light years. Recently Ghez *et al.* (2000) and Eckart *et al.* (2002) detected for the first time acceleration in the proper motions. This allows one to constrain the possible orbits around Sgr A* and locate the center of mass even better.

For one star, both peri- and apo-center passages have been observed that show a highly elliptical Keplerian orbit with an orbital period of 15.2 years and a peri-center distance of 17 light hour (Schödel *et al.*, 2002). This orbit requires an enclosed mass of $3.7 \pm 1.5 \times 10^6 M_{\odot}$. Figure 8 shows the enclosed mass as a function of the radius from Sgr A*. The solid curve is the best fit to all data points and represents the sum of a $2.6 \pm 0.2 \times 10^6 M_{\odot}$ point mass and a stellar cluster with central density $3.9 \times 10^6 M_{\odot} \text{ pc}^{-3}$, core radius 0.34 pc and power-law index $\alpha = 1.8$.

Further evidence about the nature of Sgr A* comes from its proper motion with respect to background quasars that has been measured with

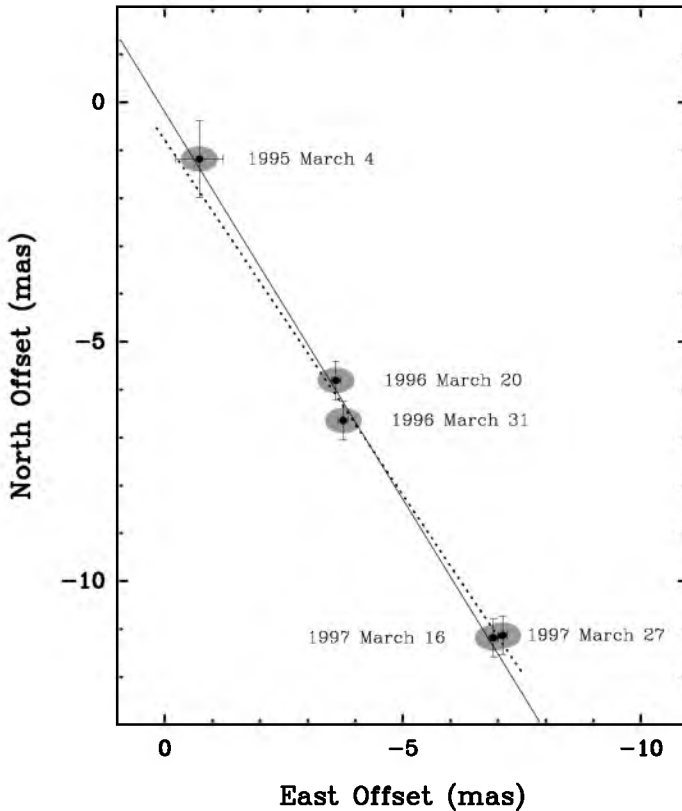


Figure 9. Proper motion of Sgr A* with respect to background quasars measured with VLBI. The solid line gives the orientation of the Galactic plane. This motion is fully consistent with the apparent motion seen due to the rotation of the solar system around the center of the Milky Way. The lack of any additional random motion of Sgr A*, despite stars being seen in fast orbits at the same position (see above), requires Sgr A* to be extremely heavy. (Taken from Reid *et al.* 1999).

VLBI. Sgr A* apparently moves with 219 km s^{-1} along the Galactic Plane (see Figure 9), which entirely reflects the motion of the sun around the Galactic Center. Hence the proper motion of Sgr A* itself is consistent with zero (Reid *et al.* 1999; Backer & Sramek 1999). This is in clear contrast to the velocities of stars in the central region which move at speeds that exceed 1000 km s^{-1} . Thus, Sgr A* has to be much more massive than

these stars and the upper limit on the speed gives a lower limit on the mass of $\sim 10^3 M_{\odot}$. Further VLBI observations (Reid and Brunthaler, 2003) and improved theoretical models (Chatterjee, Hernquist and Loeb, 2002) increase the lower limit to $\sim 10^5 M_{\odot}$.

Similar VLBI observations have also shown that Sgr A* cannot be larger than about 15 Schwarzschild radii for the given mass – just as expected for a black hole. For that reason, this is the most tightly constrained black hole candidate we know. The main difference between the center of our galaxy and those of other AGN is that Sgr A* is currently on a “starvation diet”. The accretion rate required to power its radio and X-ray emission (Falcke & Markoff 2000) is several hundred million times lower than in quasars. This was recently nicely confirmed by mm-wave polarization observations (Bower et al. 2003).

While Sgr A* is well constrained and a black hole is the least exotic model one can make (there is currently no physical object that can adequately describe all the properties of Sgr A* and its colleagues other than a black hole), the final evidence for an event horizon is still missing. However, the fact that radio interferometry has already approached the very innermost region of Sgr A* provides hope that eventually one will be able to directly image the hole.

Fortunately, Sgr A* emits strong emission at scales that are affected by general relativity. The photon orbits are bent in the vicinity of the black hole and can become circular at distances of $\sim 2 - 3R_S$. Closer orbits will end in the event horizon and produce a *shadow* in the emitting region around the black hole. Figure 10 shows the model image of an optically thin emission region surrounding a black hole with the characteristics of Sgr A* at the Galactic Center. The black hole is either maximally rotating (upper row) or non-rotating (lower row). Images (a,d) show ray-tracing calculations without any finite resolution effects taken into account, (b,e) are the images seen by an idealized VLBI array at 0.6 mm wavelength, taking interstellar scattering into account. The images (c,f) are for a wavelength of 1.3 mm. The intensity variations along the x-axis (solid curve) and the y-axis (dashed curve) are overlaid. For Sgr A*, the predicted size of this shadow is $\sim 30 \mu\text{arcseconds}$ (Falcke, Melia and Agol, 2000) and approaches the resolution of current VLBI experiments, which routinely deliver already $50 \mu\text{arcseconds}$.

Sgr A* was already detected for the first time with VLBI at 1.4 mm on one interferometer baseline (Plateau de Bure - Pico Veleta). Krichbaum *et al.* (1998) derived a source size of $0.11 \pm 0.06 \text{ mas}$ or 17 ± 9 Schwarzschild radii for a $2.6 \times 10^6 M_{\odot}$ black hole. Figure 11 shows the source size of Sgr A* versus wavelength λ . The data points follow a λ^2 behavior which is expected from scatter broadening of the image by the interstellar medium,

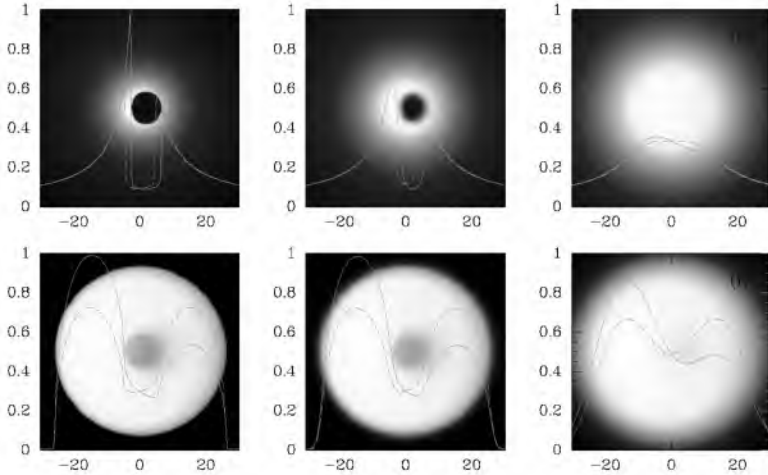


Figure 10. Shadow of the black hole event horizon as expected to be seen with future high-frequency radio interferometers. For a further description see text. (Taken from Falcke, Melia and Agol 2000).

so that the intrinsic size has to be smaller. The source size at 1.4 mm is significant larger than the scattering size and may be intrinsic. This size is just a factor of three away from the shadow. With further improvements in the technology it will soon be possible to actually make such images with the right resolution and see the event horizon.

5. Conclusions

Black holes were introduced into astrophysics as purely theoretical concepts which were needed to explain quasar luminosities. In the last years, strong evidence was found that the nuclei of non-active galaxies harbor large dark point masses, with Sgr A* being the best candidate. This is a nice and completely independent confirmation of the early theories. Indeed, the relative short history of black holes is an amazing success story: from serious doubts to almost certainty.

With high-frequency (submm-)VLBI we will soon be able to investigate their innermost being. With low-frequency observations and the revolutionary Dutch concept of a Low-Frequency Array (LOFAR)³, we will be able to discover the very first generation of black holes in the universe and learn how their enormous energy output affected our cosmos. Most of the extragalactic high energy and gamma-ray emission and possibly the ele-

³www.lofar.org

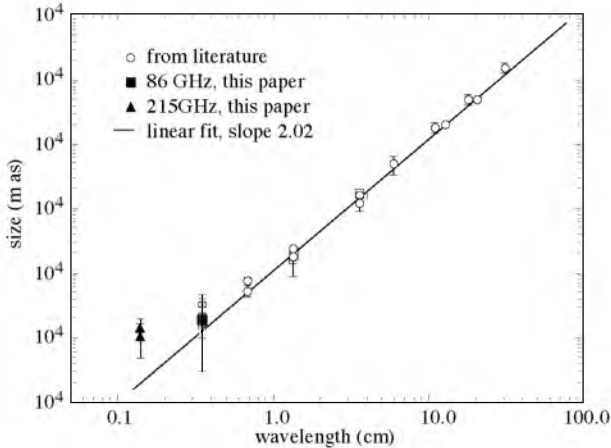


Figure 11. Size of the Galactic Center black hole Sgr A* versus observing wavelength. As interferometry has moved to higher frequencies the size and resolution has slowly approached the event horizon which is expected to become visible at 3×10^{-2} mas (lower left corner of the diagram). (Taken from Krichbaum et al. 1998).

mentary particles of the highest energies in the universe are produced by black holes. The next generation of gamma-ray and cosmic ray telescopes will thus give us also new insight into fundamental physics, thanks to these formerly exotic objects. We can be sure to still have exciting times ahead of us.

6. The “Lazarus” effect – the End of Science (again)?

Finally, I do not want to close without uttering a few random thoughts that go beyond the pure astrophysical interpretation. I will ask what impact the existence of black holes and event horizons has on our view of the world. Appropriate for a “catholic” university I will try to spice this up with a biblical story.

When I talk about black holes in public lectures, I always receive a number of very emotional responses, between fascination, awe and fear. For example, in one place, a church, I first gave a general talk about the make-up of the solar system and the universe. A year later, I was asked to come again an talk about black holes. Inspired by my first talk, one parishioner had produced a number of colorful paintings, depicting heavenly bodies. Those paintings were exhibited in the entrance hall. At the end of my black hole talk, I asked her whether we would see new paintings about

black holes at the next lecture? “No” was the answer, “black holes are frightening me - they have something dark and evil”. Indeed, Hollywood picked on that theme and created a movie called “Event Horizon”, where a black hole was even considered the entrance to hell. While the movie was not particularly outstanding, this emotional reaction in the general public is perhaps understandable, since it picks up a particularly disturbing property of black holes, which I want to describe as the “Lazarus effect”.

Black holes are a one way membrane – doors out of the known universe, that, once entered, never allow one to come back. It may well be that the “inside” of a black hole is not very different from the “outside” and is governed by the same physics. But, we will never know for sure, since no observer is allowed to relate his or her observations about the inside to the outside. In one of the very few places in the new testament where hell is actually mentioned, there is a biblical parable about a beggar named Lazarus depicting this situation. In Luke 16, 19-31 a rich man dies and is tormented in hell. Desperately he tries to warn his five brothers who are still alive. He asks Abraham, whether the beggar Lazarus who during his life time was covered with sores, longed to eat what fell from the rich man’s table, and who is now on Abraham’s side, would be sent to the rich man’s family to warn them. The wish is declined: Lazarus, the messenger, is not allowed to go back to our world — nobody would listen anyway. The only thing left for the rich man is to wait and see how his own family will eventually suffer the same gruesome fate. One by one will they come to him, without any of their cries being heard by those on the outside. This is truly hell: to be alone inside and not be able to communicate to the outside. The same is true for black holes, no message from the inside is allowed to reach the outside observer.

Scientifically, this raises some interesting questions. We are used to consider as scientific only things that can be repeatedly measured or observed in one way or the other. Proposing theories that are by definition not testable is no good scientific practice (of course, one can always hope and pray that one day they will become testable). Yet, the last century with its enormous success in the expansion of science has brought some unpleasant surprises: boundaries.

First, there was the limit of the finite speed of light. As a consequence, we are not able to know the present state of the universe, we only see its past; our view of the universe is a cone in spacetime. Then came the quantum and uncertainty limits: it is never possible to exactly determine all states of a quantum object, but one is left with an inherent and fundamental uncertainty. Next was the chaos theory: the future state of a large system of entities is not predictable even with the most precise measurements. Even the seemingly stable solar system has chaotic properties on time scales of

millions of years. It is also impossible to build a computer to indefinitely predict a future state of the universe or the solar system, since any such computer would itself influence the outcome at some level and hence would have to fully calculate itself.

Finally, we also found the boundaries of spacetime and our universe. The existence of the big bang, hence the existence of a beginning in itself (Gen 1,1) is also an end. Within the current big bang picture it is impossible to transcend that beginning with scientific means – this appears to be the end of physics and science as we know it. Of course, scientists never respect boundaries and many cosmologists try to circumvent this problem by happily proposing multiple and colliding universes. It remains to be seen whether any of this will ever be really testable or whether we will just redefine the meaning of “science” to something more mystical (back to where it was centuries ago).

Black holes play a similar role on the other end of time. They too represent a fundamental boundary. In terms of world lines they represent end-points in spacetime, just like the big bang represents a beginning. Even worse, the event horizon separates a part of the universe from direct observations (in the strict sense that this information has to be able to reach an observer in our present universe). It looks like no scientific experiment will ever be able to probe that inside. General relativists insist that mathematically the inside has a well defined solution – but is it testable science? So far, we have always relied on experiments to turn mathematical solutions into a physical reality. Are black holes the end of this kind of science, since Lazarus is not allowed to tell his story?

In that sense black holes are just an additional boundary in the list of many that modern science has found which limit our physical (and scientific) universe. I find this to be a sobering and humbling thought: just like spacetime, science may not be endless after all. Of course, perhaps a much deeper discovery is lingering below, that will let us transcend those boundaries eventually. However, so far with every new experiments all those boundaries have become even more robust. Scientifically unpenetrable boundaries may well be part of the fabric that pervades our universe and hence our lives. We may be forced to live with them.

Dank

I hope to have shown you that the study of the creation in general and of the universe and black holes in particular is an exciting and fascinating journey. A journey that is undertaken by the scientific community as a whole and by each scientist on his or her own risk.

On my personal journey to the stars I was blessed with many people

who supported me over many ways. Let me take the opportunity on this festive occasion to thank them personally.

There is my wonderful family: my wife Dagmar, my children, Jana, Lukas, and Niklas, who provide the stable framework for a rich and interesting life full of love, excitement, and many challenge of their own. There are my parents, Erika and Dr. Sigurd Falcke, who got me started and on whom I can always count for help. There is my mother-in-law, Margot Freiburg, who is an invaluable helping hand behind our daily lives.

Scientifically, I benefited a great deal from the caring wisdom of my PhD advisor, Prof. Peter Biermann (Bonn). For me, he set a shining example for excellence in science and a personal investment in young students.

I was lucky, as a postdoctoral student, to have continued finding, with Prof. Andrew Wilson (Maryland) and Dr. Anton Zensus (director at the MPIfR in Bonn), more scientists who were willing to invest time and money in an aspiring young student at crucial moments in my career – deeds I shall not forget.

Finally, I feel honored to have become part of the physics family of the University of Nijmegen. With his enthusiasm Prof. Jan Kuijpers has created a warm and positive atmosphere in the astronomy and high-energy physics department, which makes the University of Nijmegen an ideal place for research and teaching in astronomy.

Thanks be also to Prof. Harvey Butcher, ASTRON, who – very early on – realized that Nijmegen would be a good place for me. I am sure, his leadership and vision will have a lasting effect on the astronomical research in The Netherlands and beyond.

Dames en heren, ik dank u voor uw aandacht.

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