

12. Summary

THE CENTRAL REGIONS OF THE GALAXY AND GALAXIES: A BRIEF SUMMARY

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1. Introduction

This symposium has revealed considerable new progress on nuclei of galaxies over the last three years. In this talk, I will try to point out the advances since the last meeting on exactly the same subject held three years ago at Ringberg Castle in Germany (see "The Nuclei of Normal Galaxies: Lessons from the Galactic Center", ed. R. Genzel & A. Harris, Kluwer).

It was particularly timely to organize this symposium on galactic nuclei, now in Kyoto, for several important new points have come about:

- New steps in spatial resolution, due to the Hubble Space Telescope, the adaptive optics now operational, and also radio millimeter interferometers, that operate at 1mm with subarcsec beams,
- Near-infrared rapid progress in cameras and spectrographic instruments
- New results from satellites, either in X-rays, γ -rays, or far-infrared (ISO)
- Proper motions breakthrough (ESO, Keck, H₂O masers)

It is worth emphasizing that our Galactic Center is a unique laboratory, since we can probe a galactic nucleus with unrivaled spatial resolution ($1'' = 0.04$ pc; $1\text{mas} = 8$ AU for VLBI). However, our position inside the galactic plane, where we see the nuclear disk almost edge-on, is not favorable, and mutual comparisons between the Milky Way and external galaxies are necessary for a better understanding of the morphology and dynamical processes.

During all this captivating week, it has been obvious and clear why it is so interesting and rewarding to study galaxy nuclei: they are

- **Fascinating** since tremendous amounts of energy are released, either through AGN-type of activity, or through starbursts
- **Singular** In many cases, black holes are suspected to exist in nuclei because of the kinematical measurements; the density profiles are cuspy, having or not a well-defined core,
- **Unique** The center of our Galaxy is the unique place of large-scale intense magnetic phenomena. Also, for the dynamics of a galaxy, the center is the end-point of recursive dynamical phenomena, traced by nested structures like bars or spirals. These structures take over to drive the gas of the galaxy disk towards the unique center.

Although our galaxy is neither an AGN nor a starburst (and does not fall in the first category), we can take lessons applicable to external nuclei, since it has the two other characteristics.

2. Existence of Massive Black-holes (MBH)

May be the most important results that we have heard of this meeting are those confirming through proper motions the large velocities in at least two galactic nuclei (Milky Way and NGC 4258). In the Milky Way, the proper motions are stellar, seen at near-infrared wavelengths, and have been obtained over 6 years at ESO-NTT (*Eckart, Genzel*) and only one year at Keck (*Ghez*). These establish that the high velocities measured in the radial direction by spectroscopy also exist in the plane of the sky, and that the velocity dispersion is isotropic. The large velocities found around the NGC 4258 nucleus through H₂O masers seen at VLBI resolution, are also confirmed through proper motions to be compatible with rotation (*Nakai, Hernstein*). It appears now more and more certain that a black hole of $\approx 2.5 \cdot 10^6 M_{\odot}$ exists in the center of our Galaxy. Massive black-holes have stopped to play the "Arlesian", this actor of the play that never shows up, but that every people is talking about. Of course MBH were suspected long before (*Richstone*). Could compact stellar clusters still be an alternative solution to the MBH? No, certainly no for the Milky Way and NGC 4258 (*Maoz*), although a direct proof will come from measuring relativistic velocities at a few Schwarzschild radii. Many other candidates (10-20) for MBH were presented (*Ford, Richstone*), but those are not so tightly confirmed.

With the increased spatial resolution of the HST, the new discovery is the existence of nuclear disks, almost omni-present at very small scale around these active nuclei: examples are gaseous, NGC 4261, M81, M87 (*Ford*), and stellar, NGC 4342, ... (*van den Bosch*), their sizes are of the order of 100-300 pc.

In exploring the dynamics of nuclei, to deduce the possible existence of MBH, the main problem is the velocity anisotropy and existence of radial

orbits. A lot of progress has been reported in the analysis of distribution functions: three-integral models are developed, 2D fields and fine details in LOSVD (line of sight velocity distribution) are examined (*van der Marel, van den Bosch*). Even in ellipticals and early-type galaxies, links with bars and resonant rings can be made (*Emsellem*).

For the future, now that MBH have been proven to exist, many exciting questions should be considered: MBH demography (*Ho*), the MBH formation, mergers of MBH, their influence on the dynamics of the galaxy, etc... The relation between the mass of the MBH and the mass of the host-galaxy, more exactly the mass of the spheroid host (the total mass for an elliptical, the bulge mass for a spiral) has been advanced (*Richstone*), but is questionable: the scatter is about a factor 100, and observational biases are obvious. It is of prime importance to investigate such relations further to understand the formation scenarios of MBH.

There has been also considerable progress in the theory: the main puzzle of the confirmed MBH is that they are not violent AGN, in particular the activity of our own galactic center is several orders of magnitude lower than expected, from the gas present (available fuel). We have learned that there exists a magic solution, called ADAF (Advection Dominated Accretion Flow), that satisfies all observational constraints (*Narayan*). In brief, the gas is swallowed by the black hole before it has time to radiate away its gravitationally acquired energy. The constraints on thickness (H/R), or disk mass, or upper limit on perturbations of keplerian velocities are met (*Hernstein*), and may be the jet in NGC 4258 ? (*Falcke*). The spectrum of SgrA* has been successfully fit in the frame of the stellar wind accretion model (*Melia*); this model has been shown to impede accretion rate and thus solve the SgrA* puzzle (*Coker*). The spectrum can be interpreted as optically thin synchrotron emission from mono-energetic electrons in a core/shell structure (*Duschl*), or may be three structures (*Falcke*).

3. Starbursts and stellar populations

Although our Galaxy is not a starburst, there is evidence of recent star formation in the Galactic center, even though high extinction makes all results uncertain. In the central few hundred parsecs, a continuous low-level star formation has formed a flattened stellar cluster, of about a million solar masses, which is not to be confused with the center of the bulge (*Serabyn*). There is evidence of massive star formation, for instance in the Quintuplet cluster (*Nagata*), that illuminates the pistol-shaped HII regions (*Figer*), and hot dust has been mapped with ISOCAM. The clues given by the various stellar populations on the age and chemical evolution of the Milky Way bulge are hard to read (*Rich*). Long-period miras ($P > 300$ days, i.e. the

young population) are tracing the bar; but there exist also metal-rich old stars, and there does not appear any correlation between abundances and kinematics. There has been certainly recycling of stars, so that the bulge formed rapidly but not with a starburst. Many contradictions remain. A question frequently asked: are the bulge and bar the same? There is no consensus (*Ng*). The situation is quite different in M31, which appears not to have had the same history: there is a super metal-rich population of globular clusters, enlightened by recent HST studies (*Jablonka*). Very enthusiastic talks have drawn our attention on the large number of shells discovered in neutral ISM surveys (*Tsuboi, Hasegawa*). There could be as many as 500-1000 supernovae or stellar winds driven shells, attesting of a past starburst.

As for starbursts in external galaxies, a long-standing problem has been to disentangle both types of activities, from an AGN or a nuclear starburst. The predominance of one or the other is now studied with ISO SWS/LWS observations, through line ratios of highly ionized species (AGN) like OIV, and low ionised (NEII) or "PAH" features at 7μ or molecular H_2 lines (*Lutz, Egami*). An interesting study was reported about compared stellar populations in starbursts, seyferts and liners (*Joly*): the mean age of the populations appears to increase from the starbursts (logically the youngest), to seyfert 2, then seyfert 1, than liners. The existence of the two categories of seyferts would not be reducible to projection effects.

4. Singularities

The high spatial resolution of the HST has recently discovered that some spheroids possess resolved cores, while others do not. The first category corresponds to the large and luminous ellipticals, that are also predominantly boxy and triaxial, while the second category is the prerogative of the smaller ones, predominantly disk and oblate. The underlying interpretation is that the smaller ones, more rotationally supported, make the transition with spirals; throughout coalescence between smaller systems, the biggest systems lose their rotation, shape, and binary black holes can create the cores in the merging (*Makino poster*). However, we learned that in the Coma cluster, there was no effect of the environment on these two classes, and even that the bimodality character was not recovered (*de Jong*).

5. Magnetic Phenomena

The order of magnitude of the magnetic field in the galactic center is ≈ 1 mG, a thousand times higher than in the disk ($\approx 1\mu\text{G}$). The magnetic pressure ($\propto B^2$) is therefore considerable. However the gravitational force is dominant in molecular clouds (*Morris, Novak*).

The galactic center is unique for the fantastic morphology of non-thermal filaments (NTF); there are physical links between NTF, thermal filaments, molecular clouds and HII regions. The orientation of the field is completely different in the clouds and in the intercloud, and field lines reconnection at cloud surfaces could be the mechanism to accelerate relativistic electrons to produce the synchrotron emission of the NTF. The origin of this strong magnetic field could be a proto-galactic primordial field, that is amplified through gas radial inflow (*Morris*). In this domain, future progress is certainly expected in theory development, which has a wealth of observations to compare with.

6. Dynamics and Fuelling

Bars and embedded nuclear bars have been known for a long time. In theory, since gravity is scale-independent, and because these structures are gravity-driven, there is no reason not to extrapolate to even smaller structures, nested inside nuclear bars. We have heard of significant progress in spatial resolution, either from millimeter interferometers (*Tacconi, Scoville*), or adaptive optics (*Rouan poster, Knapen*), and it appears that the third-level bar structure might have been discovered already in NGC 1068. We have now improved statistics in dynamical morphologies: rings, bars, spirals, twin peaks, etc.. (*Kenney, Sakamoto*). Since these nuclear structures are usually very rich in molecular gas, it is of prime importance to settle the question of its excitation, or metallicity, which both are involved in the still uncertain CO/H₂ ratio (*Sofue, Turner, Downes*).

On the theoretical side, nested bars have been modelised, and much more details of the dynamical mechanisms are understood (*Friedli, Wada*), and models are confronted successfully to observations (*Garcia-Burillo*). We have heard that $m = 1$ perturbations are ubiquitous (*Blitz*), and new mechanisms based on non-linear wave coupling have been proposed (*Maset*). More studies should be devoted to $m = 1$ perturbation mechanisms in galaxies, that are much less well known than the $m = 2$ analogs. Future progress in this domain requires more spatial resolution to probe the micro-structures embedded into nuclear structures. This will clarify the connection between the dynamics and the AGN activity, since only micro-structures are relevant. There may be different processus of accretion and duty cycles, according to the absolute luminosity of the AGN (*Ulrich*).

I would like, on behalf of all participants, to warmly thank our chairman, Prof. Yoshiaki Sofue, for the organisation of such a fruitful meeting. We are also indebted to the co-chairmen, Reinhard Genzel and Mark Morris, and very grateful to their co-organisator, Masato Tsuboi, for very efficient time scheduling.