1. TWO HIGHLIGHTS

1.1. EFFICIENCY OF BLACK HOLE ACCRETION

R. Narayan, I.V. Igumenshchev, **M.A. Abramowicz** shown, using both analytic arguments and 3-D MHD supercomputer simulations, that black hole efficiency of converting mass to energy may approach 100% even for non argued that the accreting gas drags in a strong poloidal magnetic field to the center such that the accumulated field disrupts the axisymmetric accretion flow at a relatively large radius. Inside the disruption radius, the gas accretes as discrete blobs or streams with a velocity much less than the free-fall velocity. Almost the entire rest mass energy of the gas is released as heat, radiation and mechanical or magnetic energy. This is a practical analog of an idealized black hole engine proposed by Geroch and Bekenstein. (Magnetically Arrested Disk: an Energetically Efficient Accretion Flow, Publications of the Astronomical Society of Japan, 2003, **55**, L69)

1.2. QUANTUM PROBABILITIES

H. Westman and A. Valentini studied the origin of the Born probability rule in the de Broglie-Bohm pilot-wave formulation of quantum theory. They argued that quantum probabilities arise dynamically, and have a status similar to thermal probabilities in ordinary statistical mechanics, and illustrated this is by numerical simulations for a two-dimensional system. They proved that a simple initial ensemble with a non-standard distribution $\rho \neq |\psi|^2$ of particle positions evolves towards the quantum distribution to high accuracy. The relaxation process $\rho \to |\psi|^2$ is quantified in terms of a coarse-grained H-function (equal to minus the relative entropy of ρ with respect to $|\psi|^2$), which is found to decrease approximately exponentially over time, with a time constant that accords with a simple theoretical estimate. (gr-qc/0307040)

2. OTHER SIGNIFICANT RESULTS

2.1. RESONANCE THEORY OF THE kHz QPOs

2.1.1 **General importance of the resonance theory:** Galactic black hole and neutron star sources in low X-ray mass binaries show kHz QPOs (quasi periodic oscillations) in their observed X-ray fluxes, i.e. peaks in the Fourier variability power spectra. Many of the observed QPOs properties are rather bizarre and for this reason attract a lot of attention and simulate a lot of observational efforts, including new X-ray satellite missions. In particular, pairs of twin peaks are observed, with commensurable frequencies, most often in the ratio 3:2. Four years ago, W. Kluźniak of the Copernicus Centre and **M.A. Abramowicz** noticed that in accretion disks around black holes and neutron stars a non-linear parametric resonance may be present due to effects of super strong gravity predicted by Einstein's general relativity. They argued that vertical and radial epicyclic oscillations in resonance will modulate the emitted X-ray fluxes in a way similar to that observed in kHz QPOs. Today, the resonance explanation for the QPOs is firmly established and widely accepted. Several experts pointed out its fundamental importance for the black hole astrophysics. Later progress in the theory (in particular that in 2003 which is described in this report) was achieved through large scale supercomputer simulations, and through development of sophisticated and difficult analytic methods. The progress was done in a wide international collaboration in which a few world's best theoreticians and observers participated[1].

In 2003, the international research team working on the QPOs resonance theory consisted of:
Marek Abramowicz (professor, Chalmers, Sweden),
Wlodek Kluźniak (professor, Copernicus Centre, Warsaw, Poland),
Shoji Kato (professor, Kyoto University, Japan),
Didier Barret (professor, University of Toulouse, France),
Vladimir Karas (professor, Charles University, Prague, Czech Republic),
Zdenek Stuchlik (professor, Silesian University, Opava, Czech Republic),
Nicolaus Stergioulas (professor, Thessaloniki University, Greece),
William Lee (professor, Mexico University, Mexico),
Ron Remillard (professor, MIT, Harvard, U.S.A.),
Jeff McClintock (professor, Harvard University, U.S.A.),
Ed Spiegel (professor, Columbia University, U.S.A),
Paola Rebusco (Ph.D. student, Max-Planck-Institute, Garching, Germany),
Michal Bursa (Ph.D. student, Charles University, Prague, Czech Republic),

[1] Abramowicz's note: Due to present financial difficulties of Swedish basic research in general, and Chalmers physics in particular, it was impossible in 2003 to adequately support my costly research on QPOs by Swedish sources only. I had at my disposal very sizable research funds, much larger than those coming from Swedish sources, provided to me by a European Commission grant at the UKAFF Supercomputer Centre (Leicester University), and by a French government grant at the Institut d'Astrophysique (Paris). Substantial grants have been also provided to me by Nordita (Copenhagen), Sissa (Trieste), Silesian University (Opava), Kepler's Institute (Zielona Gora) and Copernicus Centre (Warsaw). Colleagues working with me on the QPOs resonance theory were supported in 2003 mostly by my European Commission grant at Leicester University, and also by their own research.

Jiri Horak (Ph.D. student, Charles University, Prague, Czech Republic),
Joachim Almergren (Ph.D. student, Sissa, Trieste, Italy),
Gabriel Török (Ph.D. student, Silesian University, Opava, Czech Republic).

2.1.2. **Exact mathematical formulation of the QPOs resonance theory:** Using the multiple-scale method, P. Rebusco and J. Horak found, in collaboration with W. Kluźniak, V. Karas and **M.A. Abramowicz** a general analytic solution relevant to nearly Keplerian motion, with non-Keplerianity described by a tuning parameter. This rather difficult mathematical result has several important astrophysical consequences, including the one for the ”normal branch oscillations” (NBOs) in the Z sources. Until now, the NBOs were thought to be physically distinct from the kHz QPOs. We demonstrated that a low-frequency modulation of the kHz QPOs is a natural consequence of the non-linear relativistic resonance suggested previously by us to explain the properties of the high-frequency twin peaks. Our result reproduces the 6 Hz NBOs of frequency and amplitude of the kHz QPOs reported by Yu, van der Klis and Jonker for Sco X-1. [Paper was submitted to Astrophysical Journal Letters.]

2.1.3. **Observed variability from oscillating torus:** M. Bursa, in collaboration with W. Kluźniak, V. Karas and **M.A. Abramowicz**, developed a supercomputer code to trace off-equatorial plane null geodesics in a general (numerically given) stationary, axially symmetric metric. Bursa’s code represents a significant development in this very difficult and competitive field: no such code existed previously. We used his code to calculate observed variability that is due to strong-field effects (relativistic Doppler and lensing) of almost axially symmetric, oscillating sources. This was never calculated before. For the first time one sees that a very strong luminosity modulation may be achieved in almost axially symmetric situation. [Paper will be submitted to Astrophysical Journal Letters.]

2.1.4. **Forced resonance in the millisecond pulsar:** Two simultaneous frequencies of quasi-periodic millisecond modulation of the X-ray flux (twin kilohertz quasi-periodic oscillations) have recently been detected in an accreting 2.5 ms X-ray pulsar. Their difference, equal to about $1/2$ of the neutron star spin rate, clearly indicates that resonant oscillations of the accretion disk have been observed. Similar nonlinear resonances may be spontaneously excited in the accretion disk in the absence of a pulsar, e.g., in black holes. We have identified modes of disk oscillations whose frequencies are in agreement with the two observed ones when the rotating neutron star is modeled with realistic equations of state. [This result has been obtained by W. Kluźniak, **M.A. Abramowicz**, W. Lee, N. Stergioulas and already published in Astrophysical Journal Letters.]

We have also performed numerical simulations of a radially perturbed accretion torus around a black hole or neutron star and find that the torus performs radial and vertical motions at the appropriate epicyclic frequencies. We find clear evidence that vertical motions are excited in a nonlinear resonance when the applied perturbation is periodic in time. The strongest resonant response occurs when the frequency difference of the two oscillations is equal to one-half the forcing frequency, precisely as recently observed in the accreting pulsar SAX J1808.4-3658, where the observed kilohertz quasi-periodic oscillation peak separation is half the spin frequency of 401 Hz. [This result has been obtained by W. Lee, W. Kluźniak and **M.A. Abramowicz**, and already published in Astrophysical Journal Letters.]

2.1.5. **The ULXs and intermediate mass black hole puzzle:** Recently, twin-peak QPOs have been observed in a 3:2 ratio for three Galactic black-hole microquasars with frequencies that have been shown to scale as 1/M, as expected for general relativisitic motion near a black hole. **M.A. Abramowicz**, W. Kluźniak, J. McClintock, and R. Remillard noticed that it may be possible to extend this result to distinguish between the following two disparate models that have been proposed for the puzzling ultraluminous X-ray sources (ULXs): (1) an intermediate-mass black hole M 1000 solar mass) radiating very near the Eddington limit and (2) a conventional black hole (M   10 solar mass) accreting at a highly super-Eddington rate with its emission beamed along the rotation axis. The authors suggested that it may be possible to distinguish between these models by detecting the counterpart of a Galactic twin-peak QPO in a ULX: the expected frequency for the intermediate-mass black hole model is only about 1 Hz, whereas, for the conventional black hole model the expected frequency would be the 100 Hz value observed for the Galactic microquasars. [Paper is accepted by Astrophysical Journal Letters.]

2.2. FUNDAMENTAL PHYSICS

2.2.1. **The Hartle-Thorne metric** is an exact solution of vacuum Einstein field equations that describes the exterior of any slowly and rigidly rotating, stationary and axially symmetric body. The metric is given with accuracy up to the second order terms in the body’s angular momentum, and first order in its quadrupole moment. **M.A. Abramowicz**, G.J.E. Almergren, W. Kluźniak, A.V. Thampan gave, with the same accuracy, analytic formulae for circular geodesics in the Hartle-Thorne metrics. They describe angular velocity, angular momentum, energy, epicyclic frequencies, shear, vorticity and Fermi-Walker precession. These quantities are relevant to several astrophysical phenomena, in particular to the observed high frequency, kilohertz Quasi Periodic Oscillations (kHz QPOs) in the X-ray luminosity from black hole and neutron star sources. It is believed that kHz QPO data may be used to test the strong field regime of Einstein’s general relativity, and the physics of super-dense matter of which neutron stars are made of. [Paper submitted to Classical and Quantum Gravity.]

2.2.2. **Quantum particle detectors:** S. Sonego and **H. Westman** shown that quantum particle detectors are not reliable probes of spacetime structure. In particular, they fail to distinguish between inertial and non-inertial motion in a general spacetime. To prove this, we consider detectors undergoing circular motion in an arbitrary static spherically symmetric spacetime, and give a necessary and sufficient condition for the response function to vanish when the field is in the static vacuum state. By examining two particular cases, we show that there is no relation, in general, between the vanishing of the response function and the fact that the detector motion is, or is not, geodesic. In static asymptotically flat spacetimes, however, all rotating detectors are excited in the static vacuum. Thus, in this particular case the static vacuum appears to be associated with a non-rotating frame. The implications of these results for the equivalence principle are considered. In particular, we discuss how to properly formulate the principle for particle detectors, and show that it is satisfied. [Paper already published in Classical and Quantum Gravity.]

3. PAPERS

3.1. ALREADY PUBLISHED IN REFEREED JOURNALS

Non-linear resonance in the accretion disk of a millisecond pulsar
W. Kluźniak, M.A. Abramowicz, S.Kato, W.H. Lee, N.Stergioulas
The Astrophysical Journal Letters, 603, L89-L92, 2004

Resonance in Forced Oscillations of an Accretion Disk and Kilohertz Quasi-periodic Oscillations
W.H. Lee, M.A. Abramowicz, W. Kluźniak
The Astrophysical Journal Letters, 603, L93-L96, 2004

Magnetically Arrested Disk: an Energetically Efficient Accretion Flow
R. Narayan, I.V. Igumenshchev, M.A. Abramowicz
Publications of the Astronomical Society of Japan, 55, L69-L72, 2003

Three-dimensional Magnetohydrodynamic Simulations of Radiatively Inefficient Accretion Flows
I.V. Igumenshchev, R. Narayan, M.A. Abramowicz
The Astrophysical Journal, 592, 1042-1059, 2003

Evidence for a 2:3 resonance in Sco X-1 kHz QPOs
M.A. Abramowicz, T. Bulik, M. Bursa, W. Kluźniak
Astronomy and Astrophysics, 404, L21-L24, 2003

Non-Linear Resonance in Nearly Geodesic Motion in Low-Mass X-Ray Binaries
M.A. Abramowicz, V. Karas, W. Kluźniak, W.H. Lee, P. Rebusco
Publications of the Astronomical Society of Japan, 55, 467-466, 2003

Epicyclic Orbital Oscillations in Newton's and Einstein's Dynamics
M.A. Abramowicz, W. Kluźniak
General Relativity and Gravitation, 35, 69-77, 2003

Book Review: "Black Hole Gravitohydromagnetics" by Brian Punsly
M.A. Abramowicz
General Relativity and Gravitation, 35, 1131, 2003

Det ingen vet
M.A. Abramowicz
Forskning och Framsteg, February, 2004

Particle detectors, geodesic motion, and the equivalence principle
S. Sonego, H. Westman
Classical and Quantum Gravity, 21, 433-444, 2004

3.2. ALREADY PUBLISHED CONFERENCE PROCEEDINGS

Interpreting black hole QPOs, invited lecture at *X-Ray Timing 2003: Rossi and Beyond*, Harvard, 2003
M.A. Abramowicz, W. Kluźniak
in X-Ray Timing 2003: Rossi and Beyond, ed. P. Kaaret, F.K. Lamb, J.H. Swank (Melville, NY: American Institute of Physics)

High-frequency QPOs as a problem in physics: non-linear resonance, presented at *X-Ray Timing 2003: Rossi and Beyond*, Harvard, 2003 W. Kluźniak, M.A. Abramowicz, W.H. Lee
in X-Ray Timing 2003: Rossi and Beyond, ed. P. Kaaret, F.K. Lamb, J.H. Swank (Melville, NY: American Institute of Physics)

3.3. IN PRINT AND SUBMITTED

The orbital resonance model for twin peak kHz QPOs
M.A. Abramowicz, W. Kluźniak, Z.Stuchlik, G.Török
Submitted: Astronomy and Astrophysics
astro-ph/0401464

The importance of discovering a 3:2 twin-peak QPO in a ULX or how to solve the puzzle of intermediate mass black holes
M.A. Abramowicz, W. Kluźniak, J.E. McClintock, R.A. Remillard
Accepted: The Astrophysical Journal Letters
astro-ph/0402012

Twin peaks kHz QPOs: mathematics of the 3:2 orbital resonance
P. Rebusco
In print: Publications of the Astronomical Society of Japan
astro-ph/0403341

The Hartle-Thorne circular geodesics
M.A. Abramowicz, G.J.E. Almergren, W. Kluźniak, A.V. Thampan
Submitted: Classical and Quantum Gravity
gr-qc/0312070

Of NBOs and kHz QPOs: a low-frequency modulation in resonant oscillations of relativistic accretion disks
J.Horak, M.A. Abramowicz, V.Karas, W. Kluźniak
Submitted: The Astrophysical Journal Letters

4. SUPERVISION OF DIPLOMA WORKS

4.1. DIPLOMA WORKS FINISHED IN 2003

Rotation in strong gravity
Joachim Almergren, degree obtained: Ph.D.
Sissa, Trieste
I supervised 1/2 of this work.

Risonanza parametrica di dinamiche quasi geodetiche ¡BR¿con campi gravitationali forti
Paola Rebusco, degree obtained: Laurea in Physics
Department of Physics, University of Trieste
I was an official co-supervisor of this work

4.2. DIPLOMA WORKS SUPERVISED IN 2003

Pilot wave theory
Hans Westman, degree to be obtained: Ph.D.
Göteborg University
Will be finished in 2004

Inertial forces in Einstein's general relativity
Rickard Jonsson, degree to be obtained: Ph.D.
Göteborg University
Will be finished in 2005

QPOs resonance theory
Gabriel Török, degree to be obtained: Ph.D.
Silesian University in Opava, and Chalmers (Erasmus/Socrates)
Will be finished in 2006

5. LECTURES AT SUMMER SCHOOLS

5.1. International School on "Black Holes in the Universe"

Cargse, Corsica (France) May 12-24
http://www-dapnia.cea.fr/Phys/Sap/Conferences/cargese2003/circular1.shtml

The study of black holes is currently seeing a large increase of interest in modern astrophysics. The purpose of the school "Black Holes in the Universe" is, at this timely stage, to review the current knowledge and the outstanding questions in black hole astrophysics, both observationally and theoretically. The school will mainly comprise detailed lectures given by leading experts in the field. They will be complemented by sessions of questions and answers and seminars. The school is aimed at PhD students, postdocs, and young researchers in the field in priority, and to all researchers with an interest for the school topics within the space allocation. A total number of 50 participants will be accommodated.

I had an 8 hour series of lectures "Accretion around black holes", and was a member of the School scientific committee (other members: Eric Gourgoulhon, Jean-Marie Hameury, Jacques Paul, Rachid Sunyaev). I invited Paola Rebusco to participate as a student at the School, and this gave us an ample time to work on the QPOs resonance theory.

5.2. Nordita Master Class in Physics

Den Nordiske Lejrskole, Hillerd (Denmark)
http://www.nordita.dk/conference/MasterClass2003/

Nordita organized a one-week school of physics in Hillerd (a picturesque suburb North of Copenhagen) for best students from the Nordic and Baltic countries and NW Russia region. The school aims at introducing frontier areas of physics research by world top scientists at a level understandable for undergraduate students, and also to stimulate further studies. It gives a unique possibility for students to meet outstanding scientists both in class and in informal atmosphere. The lectures will be accompanied by excercises in groups and discussion sessions.

I had a 5 hour series of lectures "Theory of accretion disks around black holes"

6. INVITED LECTURES AT CONFERENCES

6.1. Tenth Marcel Grossmann Meeting on General Relativity

Rio de Janeiro (Brazil), July 20-26, 2003
http://www.cbpf.br/mg10/WelcomeNew.html

I had two invited lectures "QPOs Resonance Theory" (30min), "Numerical simulations of accretion disks" (30min), and was a repporteur at one session (45min). I was supported by Swedish travel VR grant and by Polish KBN grant.

6.2. The 25th Aniversary of the Copernicus Centre

Warsaw (Poland), September 20-25

I had an invited lecture "Active Galactic Nuclei" (1hr). I was supported by KBN grant.

6.3. 5th RagTime Workshop

Opava (Czech Republic), 13-15 October, 2003
http://uf.fpf.slu.cz/rag/time5/

I had an invited lecture "The Ultra Luminous X-ray sources: intermediate mass black holes?" (1hr). I was supported by a special Czech grant.

6.4. X-Ray Timing 2003: Rossi and Beyond

CfA, Harvard (U.S.A.), November 3-5, 2003
http://hea-www.harvard.edu/xrt2003/

I had an invited lecture "Interpreting black hole QPOs" (30min). I was supported by Polish KBN grant.

7. SCIENTIFIC VISITS ABROAD

7.1. Institut d'Astrophysique, Paris (France)

One week in May

I was supported by the French CRNS grant.

7.2. Silesian University, Opava (Czech Republic)

August (whole month)

Note: my special Czech grant at the Opava University supported also 2 weeks vistit of J. Almergren and 4 days visit of W. Kluźniak.

7.3. Copernicus Centre, Warsaw (Poland)

Two weeks in September.

Note: during my stay at Copernicus, I participated in the *Open days of Warsaw University* and gave two public lectures during this event, rather important in Polish cultural calendar. I was supported by a Polish KBN grant.

7.4. The UKAFF Supercomputer Centre, Leicester (England)

Three months: October, November, December.

Note: my European Commission grant at the UKAFF supported also one week visits of P. Rebusco and V. Karas, 2 weeks vistits of J. Almergren and W. Kluźniak, and 6 weeks visits of M. Bursa, G. Török and J. Horak in Leicester. My European Comission grant of 13,000 British Pounds, given for three months at UKAFF, was larger than my main Swedish research grant (from VR) for the whole year 2003.

7.5. Short visits

I visited several scientific institutions in Sweden and abroad for one or two days for participation in committee meetings, lectures and participations in degree defenses: Nordita in Copenhagen, Sissa in Trieste, Stockholm University, Charles University, Cambridge University, Oxford University, Wroclaw University.