State Committee for Scientific Research – KBN For KBN use only

00-529 Warszawa Nr.

ul. Wspólna 1/3 Group

POLAND

GRANT APPLICATION

Project Title:

Galaxy formation modelling and constraints on
Dark Matter Profiles in Galaxies and Galaxy Clusters

A. APPLICANT DATA

1. Name and address of the organization where work will be performed (include department, institute, laboratory, and chair, as applicable):

Toruń Centre for Astronomy, Nicolas Copernicus University, ul. Gagarina, 11, Toruń 87-100; director prof. hab. dr Andrzej Kus

2. Principal Investigator (include title, first name, last name):

dr Boudewijn Roukema

3. Principal Investigator's employer, if different from above organization (include department, institute, laboratory, and chair, as applicable):

(same as above)

B. GENERAL DATA

1. Funding period: **36**..months (01.2005 – 12.2007)

2. Number of personnel involved in the project: **2**

3. Type of project (pick one): **Individual Project**

4. Requested funding amount (in Polish złotys Polish złoty annual 2002 mid - rate against the euro is estimated at 3,95 (Ministry of Finance - draft budget for the Year 2002) - zł):

231920 PLN

5. Keywords:

observational cosmology, galaxy formation, dark matter, dwarf galaxies, clusters of galaxies

6. **Project summary** (not to exceed 1 page; may be published by KBN if grant is awarded):

<u>Galaxy formation modelling and constraints on</u>
<u>Dark Matter Profiles in Galaxies and Galaxy Clusters</u>

Observational constraints on the values of the local cosmological parameters — the non-relativistic matter density parameter (Ω_{m}), the cosmological constant (Ω_Λ), and their sum, the total density parameter (Ω_{tot}), on length scales ranging from tens of kiloparsecs to ten Gigaparsecs — now converge to show that about 25% of the matter-energy density is composed of non-baryonic dark matter, (hereafter, "dark matter"). Many speculations exist, based on extensions of the Standard Model of particle physics, as to the nature of this dark matter, including, in particular, axions, which are bosons from CP symmetry breaking, or the Lightest Supersymmetric Particle (LSP) from supersymmetry, and many experiments are underway to try to detect these by non-astrophysical methods.

An astrophysical hint as to the nature of the dark matter is provided by the present controversy over the apparent contradictions between the theoretically (e.g. semianalytically) expected density profiles of dark matter, especially in dwarf galaxies and in clusters of galaxies, and those observed. Briefly, the problem is that the theoretical expectation is that the density profiles should be more concentrated ("cuspy") than observed (e.g. McGaugh, Barker & de Blok, ApJ, 584, 566, 2003).

In this project we propose to use and further develop existing tools in galaxy formation modelling, specifically, the ArFus software package (Roukema, Ninin, Devriendt, Bouchet, Guiderdoni & Mamon, A&A, 373, 494, 2001; downloadable here: `http://adjani.astro.uni.torun.pl/~boud/ArFus/`) and observational constraints to try to resolve this controversy. Possibilities for resolving the problem include errors in theoretical analyses, errors in observational analyses, and non-standard properties of the dark matter — for example, even though, apart from gravitational interactions, the dark matter is expected to only have very weak non-gravitational interactions with other matter, some hypotheses are that the dark matter is "weakly self-interacting" (SIDM). For example, Totani (arXiv:astro-ph/0401140) proposes that neutralino annihilation provides a heating source in the centre of galaxy clusters and thus flattening the inner part of the density profile.

We plan to investigate each of these possibilities, without prior conceptions as to which is the correct solution.

Since hot dark matter (HDM) (including massive neutrinos) can at most constitute only a small fraction of the dark matter, due to the shape of the power spectrum, we only plan to consider CDM-like (cold dark matter) hypotheses.

Galaxy formation modelling techniques such as the ArFus software enable the generation of observational statistics directly comparable with observations. The obvious problem with observing dark matter by astronomical techniques is that it is not directly observable. What is observed are the stars in a galaxy (or neutral hydrogen gas) and their motions. By modelling galaxy formation starting from cosmological initial conditions and following through all the way to observables, the implications which dark matter hypotheses (such as SIDM) have on observables can be calculated.

Much work has already been done in the study of dark matter over the past seventy years. However, despite (or because of) the enormous increase in the amount of observational data, the situation still remains very unclear. Moreover, sorting out the details of galaxy formation also remains a priority area in observational cosmology. Hence, the potential for revealing clues about the nature of dark matter and in testing standard galaxy formation hypotheses, makes this a field worthy of high priority among the many questions of modern observational cosmology.

C. STAFF INFORMATION

For the Principal Investigator and each senior staff member, provide the following biographical information:

1. *Name*

dr Boudewijn Roukema

2. *Educational history including, for each degree, the field, institution, and date obtained*

1989-93: Doctor of Philosophy (Ph.D.) in Astronomy and Astrophysics, Mt Stromlo and Siding Spring Observatories (M.S.S.S.O.), Australian National University (A.N.U.), Canberra.
1985-88: Bachelor of Science (Hons), Australian National University, Canberra, Australia (awarded National Undergraduate Scholarship for this degree)

3. *Academic and professional appointments, in reverse chronological order*

since 2002: adiunkt, Toruń Centre for Astronomy, Uniwersytet Mikołaja Kopernika, Toruń, Poland
2001: visitor, DARC/LUTH (Laboratoire de l'Univers et ses Théories), Observatoire de Meudon, France
1998–2000: postdoctoral fellow, Inter-University Centre for Astronomy & Astrophysics, Pune, India
Feb–July 1998: visitor, CAMK, Warszawa
1996–1997: Centre of Excellence foreign visiting fellow, NAOJ, Mitaka, Tokyo, Japan
1994–1995: postdoctoral research fellow, Astronomy Centre, University of Sussex, U.K.
Jan/Feb 1994: visitor, Institute of Astronomy, University of Cambridge, United Kingdom
1993: postdoctoral fellow, Institut d'Astrophysique de Paris, CNRS, France

4. *Brief descriptions of research projects completed in the last four years, including up to 10 publications (provide publication data).*

Main Research Interests
(i) *Observational Cosmology* and (ii) *Galaxy Formation*: (i) Observational constraints on statistics of "large scale" structure, observational constraints on local cosmological parameters (such as the density parameter and the cosmological constant), and observational programmes to try to constrain global cosmological parameters; (ii) Merging-history-tree based galaxy formation models in a cosmological context and their comparison with observational galaxy statistics.

1 Roukema, B.F. & Bajtlik, S., 1999. *Transverse Galaxy Velocities from Multiple Topological Images, Monthly Notices of the Royal Astronomical Society,* **308,** 309 (arXiv:astro-ph/9903038)

2 Roukema, B.F., 2000a. *COBE and Global Topology: An Example of the Application of the Circles Principle, Monthly Notices of the Royal Astronomical Society,* **312,** 712 (arXiv:astro-ph/9910272)

3 Roukema, B.F. & Mamon, G.A., 2000. *Tangential Large Scale Structure as a Standard Ruler: Curvature Parameters from Quasars, Astronomy & Astrophysics,* **358,** 395 (arXiv:astro-ph/9911413)

4 Roukema, B.F., 2000b. *A Counterexample to Claimed COBE Constraints on Compact Toroidal Universe Models, Classical and Quantum Gravity,* **17,** 3951 (arXiv:astro-ph/0007140)

5 Roukema, B.F., 2000c. *The Topology of the Universe, Bulletin of the Astronomical Society of India,* **28,** 483 (arXiv:astro-ph/0010185)

6 Roukema, B.F. & Mamon, G.A., 2001. *Lifting cosmic degeneracy within a single data set, Astronomy & Astrophysics,* **366,** 1 (arXiv:astro-ph/0010511)

7 Roukema, B.F., 2001b. *How to distinguish a nearly flat Universe from a flat Universe using the orientation independence of a standard ruler, Astronomy & Astrophysics,* **369,** 729 (arXiv:astro-ph/0102095)

8 Roukema, B.F., 2001d. *On the comoving distance as an arc-length in four dimensions, Monthly Notices of the Royal Astronomical Society,* **325,** 138 (arXiv:astro-ph/0102099)

9 Roukema, B.F., Ninin, S., Devriendt, J., Bouchet, F.B., Guiderdoni, B., Mamon, G.A., 2001. *Star Formation Losses Due to Tidal Debris in 'Hierarchical' Galaxy Formation, Astronomy & Astrophysics,* **373,** 494 (arXiv:astro-ph/0105152)

10 Roukema, B.F., Mamon, G.A., & Bajtlik, S., 2002. *The Cosmological Constant and Quintessence from a Correlation Function Comoving Fine Feature in the 2dF Quasar Redshift Survey, Astronomy & Astrophysics,* **382,** 397 (arXiv:astro-ph/0106135)

5. *Awards received*

D. PROJECT DESCRIPTION, METHODOLOGY, AND EXPECTED RESULTS

What problem is being proposed and why? Why should this work be undertaken in Poland?

The problem being posed is to compare the theoretical role of non-baryonic dark matter in galaxy formation and the observational constraints, specifically in the context of non-baryonic dark matter density profiles in galaxies and clusters of galaxies.

It is posed because about 25% of the matter-energy density in the Universe consists of at least one type of particle which has never been detected in any laboratory. This "non-baryonic dark matter" has been detected by its gravitational effects on astrophysical objects on many length scales, and it is quite likely that better galaxy formation modelling may yield further constraints on the nature of this unknown particle (or particles).

This work should be undertaken in Poland because there is a strong history of major astronomical discoveries in Poland, which we would like to continue.

What is the present state of knowledge in the field, and to what extent does this project verify it? How will the project advance discovery and understanding in its field or across fields? Is this a new or a continued problem?

The present state of knowledge regarding dark matter density profiles in galaxies and clusters of galaxies is that many observations of galaxies and clusters seem to show that the inner parts of the density profiles are flatter (less concentrated) than expected from the classical Navarro, Frenk & White (ApJ, 462, 563, 1996) density profile:

$$\frac{\delta(r)}{\delta_{\mathrm{crit}}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2} \tag{1}$$

found from N-body simulations, where $r_s = r_{200}/c$ is a radius depending on the virialisation radius r_{200}, c is a concentration parameter, and δ_c directly depends on c with no free parameters. Although the central slope here is flatter than in the outer regions, it is still much steeper than observations.

We do not know in advance whether or not the project will support or falsify the theoretically expected density profiles.

It is hoped that the project will advance discovery and understanding of galaxy formation by finding out the nature and possible cause of the discrepancy between theory and observations of density profiles, and also how properties of the dark matter particles — not yet detected in Earth-based laboratories — can affect observational constraints.

Possible consequences could be clues to the nature of non-baryonic dark matter, which are complementary to those which could be obtained by direct detection experiments (scattering cross section for a given target nucleus and particle mass) such as density of cold dark matter in galaxies and clusters of galaxies, and moreover, can serve as inputs to those experiments.

The observational constraints to be used come from a wide variety of extragalactic observations (such as the SDSS, the 2dF galaxy and quasar surveys, gravitational lensing, optical and radio rotation curves of close and distant galaxies) and H I clouds .

The general dark matter problem dates back about seventy years, but the cusp problem is only about half a decade old. (The Navarro-Frenk-White density profile of 1996 plays a major role in this field.)

What is the proposed methodology? How will it solve the problem? What equipment will be used? Does the applicant have the required equipment skills and access?

The methodology is to use and further develop the ArFus "hybrid" galaxy formation software (downloadable here: `http://adjani.astro.uni.torun.pl/~boud/ArFus/`), and to test the various theoretical and observational claims.

There is no guarantee that it will solve the problem, but it is likely that it will make a few steps in the right direction.

Equipment required includes good computing resources, both in hardware and software. We have one version of the software (ArFus), we might also use others.

While we have enough hardware to get started on the project, we are applying for the purchase of four computers in order to form a computer cluster and have higher CPU computational power available for simulations.

Boudewijn Roukema has extensive experience in the specific software package ArFus, and Bartosz Lew has general experience in computer simulations in multi-tasking systems, in particular from analysing the WMAP microwave background data.

What are the expected results of this project ("know-how", patents, methods, equipment), and how will they be disseminated (publications, conference presentations, PhD theses)?

Expected results could be a resolution of the cusp problem, for example, finding that theory incorrectly predicts highly concentrated density profiles, for example, due to oversimplification of input physics, or confirmation of the problem and improved understanding of what properties of dark matter could lead to obtaining consistency with the observations.

Articles on the results will of course be published in refereed journals, presented at conferences, and professionals and non-professionals will be able to follow (and maybe participate) in the research on our web pages via the normal methods of internet culture such as publicly archived mailing lists and wiki pages (`http://pl.wikipedia.org/wiki/Wiki`).

E. SOLICITED PROJECTS ONLY: DOES THE APPLICANT MEET THE CALL CRITERIA, PARTICULARLY THOSE CONCERNING INTERNATIONAL COOPERATION?

N/A

F. PROJECT SCHEDULE - ANTICIPATED TASKS

No.	Name and description of task	Expected completion date (mm/yy)	Expected cost (zł)
1	updating ArFus to work on computer cluster	6/2005	5900 PLN
2	dark matter density profiles in dwarf galaxies	12/2005	5900 PLN
3	purchase computer items	12/2005	65000 PLN
4	international cosmology consultants	12/2005	18000 PLN
5	conferences, public relations	12/2005	13000 PLN
6	indirect costs	12/2005	12840 PLN
7	modelling dark matter density profiles in clusters	6/2006	5900 PLN
8	refining "observational" outputs of ArFus	12/2006	5900 PLN
9	international cosmology consultants	12/2006	18000 PLN
10	conferences, public relations	12/2006	13000 PLN
11	indirect costs	12/2006	12840 PLN
12	coding self-interacting dark matter in ArFus	6/2007	5900 PLN
13	analysing self-interacting dark matter hypothesis	12/2007	5900 PLN
14	international cosmology consultants	12/2007	18000 PLN
15	conferences, public relations	12/2007	13000 PLN
16	indirect costs	12/2007	12840 PLN
Total			231920 PLN

G. PROPOSED BUDGET

No. Item	Funds for each budget year (zł)			Total
	2005	2006	2007	
1 Direct costs, including:				
1/ Salaries and benefits	11800	11800	11800	35400 PLN
2/ Equipment	65000			65000 PLN
3/ Other direct costs				
international cosmology consultants	18000	18000	18000	54000 PLN
conferences, public relations	13000	13000	13000	39000 PLN
Subtotal:	107800	42800	42800	193400 PLN
2 Indirect costs (admin costs to UMK - 30% (1/ + 3/))				
	12840	12840	12840	38520 PLN
3 Total costs (1+2)	120640	55640	55640	231920 PLN

Details of direct cost items

1) *Salaries and benefits*

Principal Investigator **18** *person-months*

Based on KBN guidelines, 100% of 11800PLN/annum for the principal investigator if dr., 75% for other investigators if dr., 50% of 11800PLN/annum for other investigators if mgr. However, for this project we choose to give equal rates to both participants, i.e. at the 50% rate.

Hence:

(i) dr Boudewijn Roukema 5900 PLN *3 = 17700 PLN

Staff **18** *person-months*

(ii) mgr Bartosz Lew 5900 PLN *3 = 17700 PLN

Total: 35400 PLN

2) *Equipment (type, estimated cost, planned month of purchase, and justification)*

Justification: Galaxy formation modelling and constraining the role of dark matter in galaxy centres requires intensive computing power. We also need computer facilities for presentations at seminars, conferences and other public relations actions.

Purchases are planned for 2005.

(i) computer cluster for simulations - four computers + 3yrs insurance (loss/theft/etc.) 28 kPLN

(ii) 2 uninterrupted power supply units (UPS), each costing 1600 PLN, total= 3200 PLN

(iii) computer for analysis of simulations (B. Lew) 7 kPLN

(iv) computer for analysis of simulations (B. Roukema) 7 kPLN

(v) portable computer ("notebook") + 3yrs insurance (loss/theft/etc.) 10 kPLN

(vi) inkjet scanner/copier/printer + 3yrs insurance (loss/theft/etc.) (an inkjet PSC 750 costs 900 PLN; recycled cartridges cost about 35 PLN B/W, 50 PLN colour) 1 kPLN

(vii) colour laserwriter/scanner/copier + 3yrs insurance (loss/theft/etc.) 7 kPLN

(viii) paper + ink for inkjet + laserwriter 2 kPLN

Total: 65000 PLN

3) *Other direct costs (type of expenditure, amount, and relation to project plan)*

These relate to the project plan in that the project is internationally competitive research and so (1) international consultants are required for providing constructive criticism and analysis of our approach, and (2) we need to be able to present our results at international conferences and consult international experts at their home research institutes.

(1) The research environment for an internationally competitive research project requires consultations from international experts for periods of between 1 week and a few months. Three people each for one month, and four people each for a week, per year, yields a total of 12 person-months over the three-year period of the project.

At a rate of 4500 PLN/month for international consultants in cosmology, we have

Total: 54000 PLN

(2) In order to present our results at conferences and other public relations exercises, attendance at two international conferences per fractional person per year would be consistent with international standards.

One conference: international (Europe, US) typical economy class train travel [1] (or air travel) within Europe, or air travel to US, is typically 2 kPLN; intercontinental economy class air travel (India/Japan/Australia) ranges up to 10 kPLN; so a median of 3.5 kPLN is a conservative compromise. One week's accommodation and per diem in Europe/US/Japan/Australia (2 kPLN) + registration fees (1 kPLN) ⇒ 6500 kPLN. Hence, two conferences/year for a 100% person are within the recommended spending limits.

At a rate of 2 conferences per year per effective person, and 1.0 total effective people, over 3 years, this implies:

Total: 39000 PLN.

To maximise transparency and accountability, while retaining flexibility, all committee members are welcome to participate in our publicly archived mailing list with scientifically useful comments, suggestions and/or criticisms:
`http://www.astro.uni.torun.pl/sympa/cosmo-torun`

[1] See `http://www.grida.no/climate/ipcc_tar/wg1/fig2-20.htm` for arguments in favour of train travel

Date	*Grantee organization*		*Principal Investigator*;
	Kierownik: Prorektor ds Nauki i Współpracy z Zagranicą prof dr. hab. Marek Zaidlewicz	Kwestor mgr Henryk Heldt	dr Boudewijn Roukema
	Signature	Signature	Signature