ISBN 978-0-7354-0786-2
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ISBN 978-0-7354-0786-2
ISSN 0094-243X

Debattista
Popescu

HUNTING FOR THE DARK:
THE HIDDEN SIDE OF GALAXY FORMATION

AIP CP
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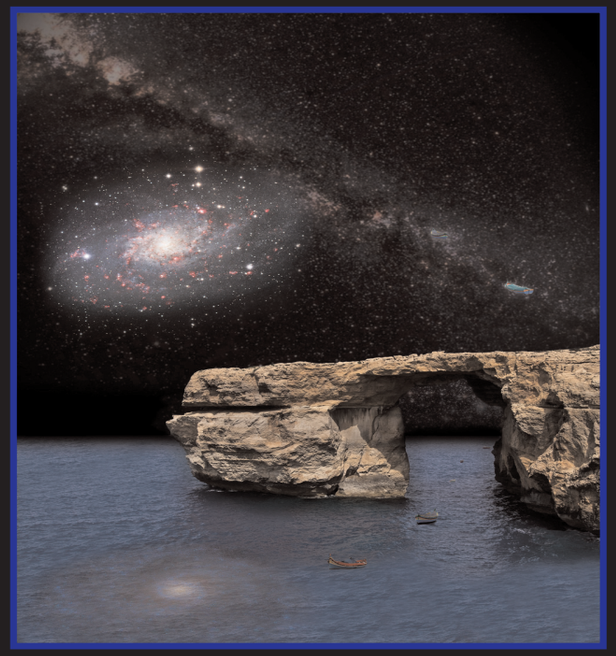
Proceedings of the International Conference

19-23 October 2009
Qawra, Malta



*EDITORS*

*Victor P. Debattista and Cristina C. Popescu*

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Victor P .Debattista
Cristina C.Popescu
*University of Central Lancashire,UK*

**SPONSORING ORGANIZATIONS**
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AIP American Institute of Physics

**Melville, New York, 2010**
**AIP CONFERENCE PROCEEDINGS ▮ 1240**

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L.C. Catalog Card No. 2010904056

ISBN 978-0-7354-0786-2

ISSN 0094-243X
Printed in the United States of America

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## PREFACE

The international conference "Hunting for the Dark: The Hidden Side of Galaxy Formation" was held in Malta 19-23 October 2009 at the Dolmen Hotel situated on picturesque Qawra Bay. The meeting was organised by the University of Central Lancashire and the University of Malta, providing a forum for 140 scientists from 22 countries. The scientif c programme included 13 invited talks, 62 contributed talks and over 50 poster presentations.

The meeting was born from the wish to bring together diverse communities of researchers working on unravelling the complicated processes by which galaxies form. Many of the components and processes that play an important role in the formation of galaxies are either dark, obscured or faint. Testing theories and models is therefore a challenging task; it was this challenge that the conference sought to address. The topics addressed by the meeting included the properties of dark matter halos in disk, elliptical and dwarf galaxies, supermassive black hole formation and growth, the scaling relations of supermassive black holes, nuclear star clusters and bulges, stellar halos and tidal debris, disk outskirts, dust enshrouded star formation, the effect of dust on spectral energy distributions, hot and cold accretion onto galaxies, hot gas halos and gas circulation.

A signif cant number of new theoretical and observational results were presented and discussed at the workshop. Theorists presented models spanning a large range of scales and complicated physics, while observers, not to be outdone, spanned the entire spectral range from radio, through to infra-red, optical, UV and X-rays. Judging from this we feel that we have achieved our goal of bringing together many of the diverse communities working on galaxy formation.

We would like to thank all the participants for making the meeting as stimulating and exciting.

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## ACKNOWLEDGEMENTS

This meeting would not have been possible without the help of a large number of people. Much valuable advice on the science content of the meeting was provided by the Scientif c Organizing Committee which was comprised of Andi Burkert (University of Munich, Germany), James Bullock (University of California at Irvine, USA), Francoise Combes (Observatoire de Paris, France), Victor Debattista (chair, University of Central Lancashire, UK), Michael Dopita (Australian National University, Australia), Simon Driver (University of St. Andrews, UK), Annette Ferguson (University of Edinburgh, UK), Ken Freeman (Australian National University, Australia), Karl Gebhardt (University of Texas at Austin, USA), Ben Moore (University of Zurich, Switzerland), Cristina Popescu (chair, University of Central Lancashire, UK) and Richard Tuffs (Max Planck Institut für Kernphysik, Germany). Their input was instrumental in bringing together such an exciting mix of diverse communities.

We were very fortunate to have had a Local Organizing Committee that was always able to solve any logistical problem we encountered. At the University of Malta, Pierre-Sandre Farrugia deserves particular mention for his indefatigable work to ensure a successful, and enjoyable, meeting. Thanks to him, a host of Boojums that may have plagued the conference never materialized. At the University of Central Lancashire, the conference secretary, Emma Kelly, worked tirelessly to insure the smooth running of the conference. Additional help was provided by the remainder of the LOC: Edward Mallia, Joseph Caruana (who designed the conference poster), Pauline Galea, Matthew Agius and Ray Pace. Additional volunteers during the conference included Monica Micallef, David Grech, Jackson Said, Yury Kulakov, and Alessio Magro. Assistance with the editing of these proceedings by Bogdan Păstrăv, Dmitrij Semionov and Marina Debattista is gratefully acknowledged.

The assistance of Patricia Camilleri through the Communication Off ce of the University of Malta is also gratefully acknowledged. Our thanks also go to Professor Anthony Bonanno, chair of the Department of Archaeology of the University of Malta for his delightful lecture on the Maltese Neolithic.

We would also like to acknowledge the University of Malta, in particular the Chair of the Physics Department and Dean of Science, Professor Charles Sammut, for the considerable support, both f nancial and human. The support we received from the University of Central Lancashire, and most especially the encouragement from the Head of the Jeremiah Horrocks Institute, Professor Gordon Bromage, allowed us to focus our energies on the main issues.

We are also very grateful for the sponsorships we received. The Malta Council of Science and Technology, headed by Nicholas Sammut, was an early and generous supporter of the meeting. The sponsorship from Heritage Malta allowed the conference attendees to experience a small part of the rich cultural heritage that Malta has to offer. A sponsorship from the Royal Astronomical Society allowed a number of students to attend the conference; for many of these attendence was a signif cant step in their careers. Further sponsorships were provided by Toyota, Farsons, Air Malta, the St. Paul's Bay town council, and the Malta Tourism Authority.

# Welcome Address

Gordon Bromage

*Jeremiah Horrocks Institute, University of Central Lancashire, UK*

Good morning, ladies and gentlemen. Welcome to this international conference entitled "Hunting for the Dark – the Hidden Side of Galaxy Formation", in this splendid location on the beautiful island of Malta.

I have great pleasure in welcoming you here, on behalf of the Vice-Chancellor of the University of Central Lancashire and all the astronomy staff of the Jeremiah Horrocks Institute at UCLan, and on behalf of the conference's organising committees. Welcome to this Hunt: for the Dusty; for the Elusive; for the Faint; for the Invisible; for the Obscured; for the Undetected Dark. It is certainly a challenging yet exciting task.

If you read Lewis Carroll's surreal rhymes in his "Hunting of the Snark", you may, like me, recognise quite a few parallels with our own Hunt, and take some amusement from this, as the conference organisers realised some time ago. You might be a pessimist and even entertain a notion – "a faint but wildly possible notion" – that at the end of this Hunt we may be unfortunate enough to catch a Boojumino for our Dark Matter Particle, and then "softly and suddenly vanish away". Let us sincerely hope that we are infinitely more successful than that.

To guide us, let us first look back in time along our hunting trail. We can trace it back seventy or eighty years to two crucial revelations in the history of astrophysics. First, we remember Trümper's famous demonstration in 1930 of the importance of interstellar dust, from observations of open star clusters in the Milky Way. Secondly, there were Babcock's and Oort's studies of the mass-to-light ratios in the outer regions of disks of nearby galaxies such as M31. In a retrospectively famous section of Oort's talk at the dedication of the McDonald Observatory in Texas in 1939, he said (and I extract from his words here, for reasons of brevity): "The distribution of mass ... appears to bear almost no relation to that of the light. ... In the outer parts of the nebula, the ratio of mass density to light density is found to be very high, and this conclusion holds for whatever dynamical model we consider..."

So the trail of Dark and Hidden Matter could be said to start in earnest at least 70 years ago. It has followed a winding path to the present day, with many twists and turns. Well, after 70 years, do we like those on the Snark Hunt, "shudder to think that the chase might fail"? No – absolutely not, of course, because we are eternal optimists: we are astronomers and astrophysicists, after all, and moreover great progress has been made in recent years towards our goal. I am reminded here of a recent article, a leading article in the UK's Guardian newspaper last July, written (obviously, but please note) by a non-astronomer, and entitled "In Praise of... Astronomers". I would like to quote

some extracts here: and you may want to find this article, frame it and put it on your office wall, for those bad days when things seem to be going wrong in your hunt for the truth. "They usually work alone, and in dark places, but they have lit up our universe. Skywatchers began as guardians of clock and calendar, compiled our tide tables and pioneered modern navigation. They devised instruments, invented the science of optics, and minted the mathematics to explain the phenomena they observed. From Eratosthenes of Alexandria... 2200 years ago [to today], astronomers are part of an epic story of wide-eyed discovery... Astronomers around the world compete, co-operate and confer; they are a global community, in the richest sense of the term, and we owe them our understanding of space and time, and light, and mass, and gravity: in a word, everything." (from The Guardian, Editorial, Saturday 25 July 2009).

We who are Hunting for the Dark certainly comprise a truly global community: I am very impressed and pleased to note that there are delegates here from no fewer than 22 different countries! And we are here to compete, co-operate and confer on the Hidden Side of Galaxy Formation.

Now I would like to briefly allude to a most remarkable young role-model astronomer from one short period in the 2200-year-long history of our science, this very long history referred to by the Guardian leader-writer. There may well be some delegates here who are unfamiliar with the work of Jeremiah Horrocks, after whom we named our Astrophysics Institute at UCLan. He was on a quite different hunt from the present one, but I believe he provides much valuable inspiration for us on our hunt for the Dark. Horrocks lived and worked in Lancashire nearly 400 years ago. He performed his most famous observations and calculations in 1638-9 just a few kilometres from our Institute in Preston. His story is a quite fantastic one, providing an inspiration especially to students and young astronomers. Since some of you may be unaware of the story, let me tell you some of the highlights. A poor scholar working as a tutor in rural Lancashire, he performed his key work between the ages of 18 and 22. He died suddenly in Liverpool at the age of only 22 or 23, but it is no exaggeration to state that he inaugurated English research astronomy, just a few years after the famous work of Kepler and Galileo. He was the first to correctly determine the lunar orbit as an ellipse, based on his own observations, at age 20. He was the first to successfully predict and observe a transit of Venus across the face of the Sun – a phenomenon crucial for determining the size-scale of the universe – in deepest rural Lancashire with amateur equipment, observing the Sun in the middle of a northern-English cloudy winter, and where Kepler and everyone else had failed. Newton sang his praises in the "Principia". Allan Chapman, distinguished historian of astronomy at Oxford, has said that Horrocks provided a linch-pin in the development and understanding of gravity (very relevant to our present Hunt this week, of course) between Kepler and Newton.

But now let us come back swiftly to 2009. We should take inspiration, then, from many past hunts in astronomy, and keep hunting with all the resources at our disposal. After the conference this week, let us hope that we are able to say of our quarry (with apologies again to Lewis Carroll): "We sought it with Surveys, we sought it with care;/ We pursued it with Halos and hope;/ We threatened its life with a Baryonic Pair;/ We charmed it with Spitzer and ... Initial Mass Functions and Star Formation Histories".

I wish you a most successful and enjoyable conference here in Malta.

# Galactic Fountains and Gas Accretion

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**Abstract.** Star-forming disc galaxies such as the Milky Way need to accrete $\gtrsim 1\,M_\odot$ of gas each year to sustain their star formation. This gas accretion is likely to come from the cooling of the hot corona, however it is still not clear how this process can take place. We present simulations supporting the idea that this cooling and the subsequent accretion are caused by the passage of cold galactic-fountain clouds through the hot corona. The Kelvin-Helmholtz instability strips gas from these clouds and the stripped gas causes coronal gas to condense in the cloud's wake. For likely parameters of the Galactic corona and of typical fountain clouds we obtain a global accretion rate of the order of that required to feed the star formation.

## THE PROPOSED SCENARIO

Star-forming disc galaxies like the Milky Way must accrete $\gtrsim 1\,M_\odot$ of fresh gas each year [see 1, and references therein] and have built their discs gradually over the last 10 Gyr [e.g. 2]. A central question is the origin of the accreted gas and how this gas reaches the thin disc whithin which the process of star formation takes place. The virial-temperature corona, in which disc galaxies are embedded, is the only reservoir of baryons capable of sustaining an accretion rate of $\sim 1\,M_\odot\,\mathrm{yr}^{-1}$ for a Hubble time. We present the results of a set of grid-based hydrodynamical simulations supporting the idea that the gas needed by the disc to form stars is drawn from this corona.

Coronae of disc galaxies are similar in many respects to the hot atmospheres of giant elliptical galaxies and galaxy clusters, but with lower gas temperature and density [e.g. 3, 4]. As the hot gas of these more massive systems, the coronal gas is unlikely to fragment into clouds via thermal instability [5], but it is expected to cool monolithically and feed the central black hole rather than produce an extended cold disc in which stars can form. However, if the gas needed to feed star formation has to be drawn from the corona, a mechanism that makes the hot gas accrete onto the disc must be at work.

There is abundant evidence that star formation in galaxies like the Milky Way powers a galactic fountain: ejection of gas from the mid-plane by supernova explosions [6]. Through the fountain a significant fraction (from 10 to 25 %) of the whole HI content of the galaxy is carried into its halo [see 7, and references therein]. In this work, supported by several lines of argument, we hypothesise that the transfer of gas from the corona to the star-forming disc is effected by the HI clouds ejected by the galactic fountain [8].

Our hydrodynamical simulations suggest that the gas accretion proceeds through the following steps: (i) stripping of gas from fountain clouds by the corona as a result of the Kelvin-Helmholtz instability, (ii) mixing of the (high metallicity) stripped gas with a

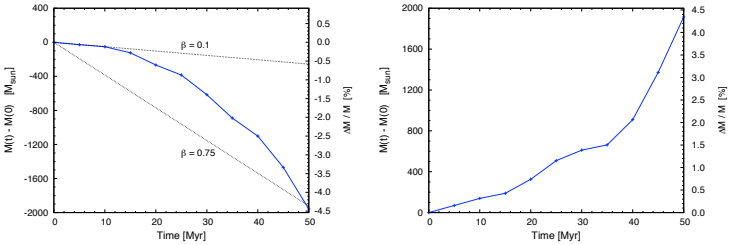


**FIGURE 1.** The evolution of the mass of gas at $T < 5 \times 10^5$ K when radiative cooling is switched off (left panel) or on (right panel). The dotted straight lines show two estimates of critical mass-loss rate $\alpha_{\rm crit}$. The particle density of the corona is $2 \times 10^{-3}{\rm cm}^{-3}$, its temperature $2 \times 10^6$ K and the metallicity of the system is [Fe/H] $= -1.0$.

comparable amount of coronal gas in the turbulent wake of the clouds; as a consequence of the mixing, the gas cooling time of the coronal gas is reduced to a value lower than the cloud's flight time, (iii) formation of knots of cold gas that accrete onto the disc in a dynamical time.

The stripped gas leads to condensation of coronal gas only if the mass-loss rate exceeds a critical value $\alpha_{\rm crit}$, determined by the physical properties of the cloud and the corona. In addition, dimensional analysis suggests that the actual mass-loss rate must lie close to $\alpha_{\rm crit}$. In view of the proposed scenario and of these considerations the aims of the simulations are two-fold: (i) to provide an estimate of the actual mass-loss rate $\alpha$ for comparison with $\alpha_{\rm crit}$, (ii) to determine the critical ambient pressure (dependent on metallicity) above which the mass of cool gas increases with time through condensation in the wake. In figure 1 the evolution of the mass of gas at $T < 5 \times 10^5$ K (accreted gas), for a simulation with physical conditions representative of galactic coronæ, is shown (see caption for details). In particular, in the left panel of the figure, the mass loss of a cloud is displayed and the agreement between the simulation and the analytical prediction is remarkable. From the right panel of figure 1 it has been possible to derive an estimate of the global accretion rate ($\approx 0.5 M_\odot\,{\rm yr}^{-1}$) which is of the same order as that required to feed star formation. By comparing the figures in the two panels it is apparent that the cooled mass of coronal gas is comparable to the mass lost by the cloud. In other words, when the cooling is switched on, the evaporation of some cloud mass produces an accretion of roughly the same amount of coronal mass.

## SUMMARY AND CONCLUSIONS

We have used hydrodynamical simulations to check whether the interaction between the galactic-fountain clouds, powered by a star-forming disc, and the virial-temperature corona, in which disc galaxies are embedded, could lead the coronal gas to cool promptly in the clouds' wake and accrete onto the disc to feed star formation. The results of our analysis, described in detail in [8], can be summarized as follows:

- the interaction between the galactic fountain and the hot corona causes the fountain clouds to be stripped of some of their gas. The simulations provide a reliable estimate of the mass-loss rate and confirm that its value lies close to $\alpha_{\rm crit}$, in

agreement with analytical expectations;

- the condensation of coronal gas in the cloud's wake prevails over evaporation if the metallicity and/or pressure of the corona are high enough. In our simulations this happens for likely parameters of the coronæ in disc galaxies, where condensation is present also for densities as low as $n_{\rm h} \simeq 4 \times 10^{-4} {\rm cm}^{-3}$, provided that [Fe/H] $\sim 0$;
- the derived global accretion rate is of the same order as that required to feed star formation. Therefore the condensation of the hot corona seems a viable mechanism to sustain the star formation rate in star-forming galaxies.

## ACKNOWLEDGMENTS

We used CPU time assigned under the INAF-CINECA agreement 2008-2010. F. Marinacci gratefully acknowledges the support from the Marco Polo program by University of Bologna and the hospitality of the Rudolf Peierls Centre for Theoretical Physics.

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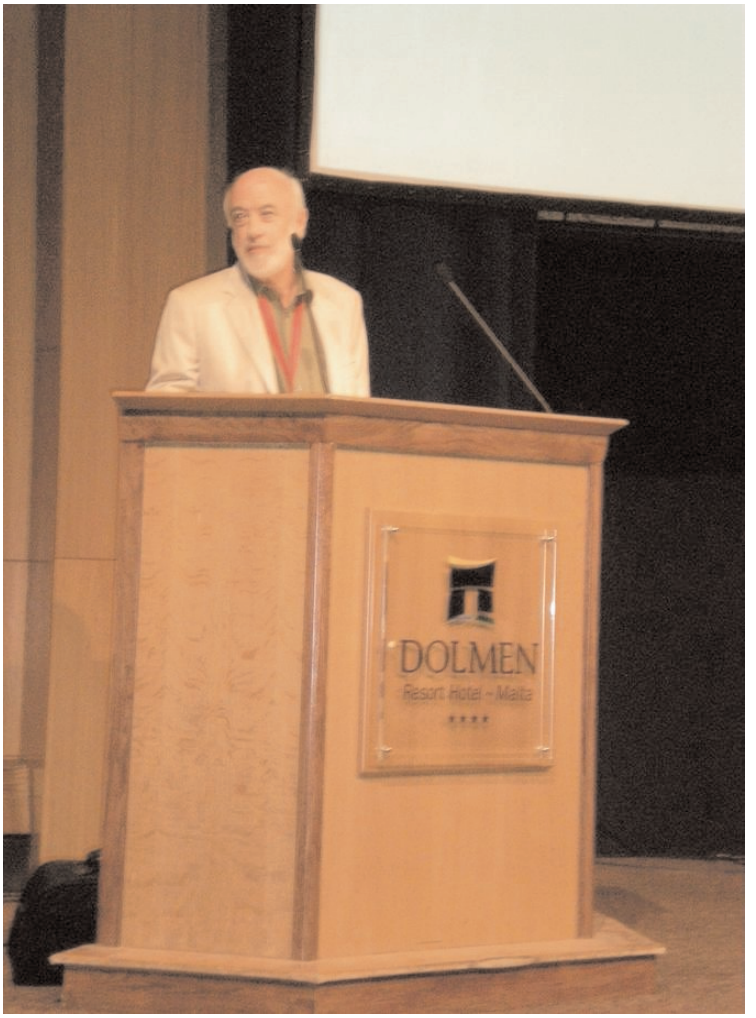
# PHOTO GALLERY

Neal Katz and Ben Moore getting ready for the opening session.

Piet van der Kruit, Ken Freeman, Olga Sil'chenko,
and Alexei Moiseev during the first session.

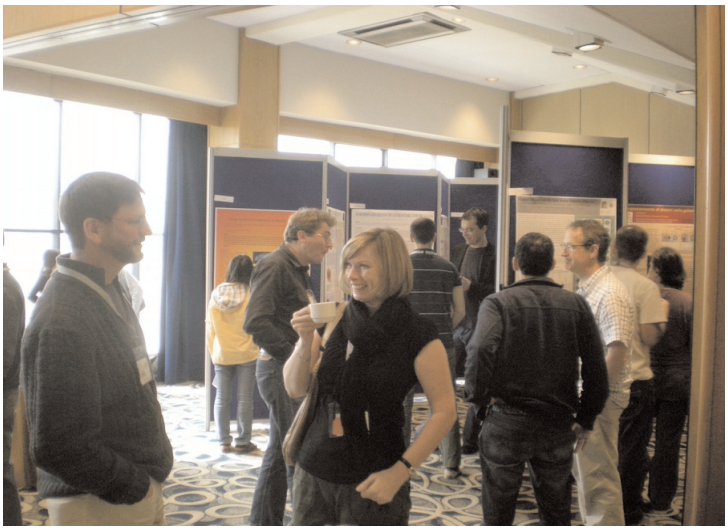



Gordon Bromage welcomes the hunters and wishes them well on their quest.

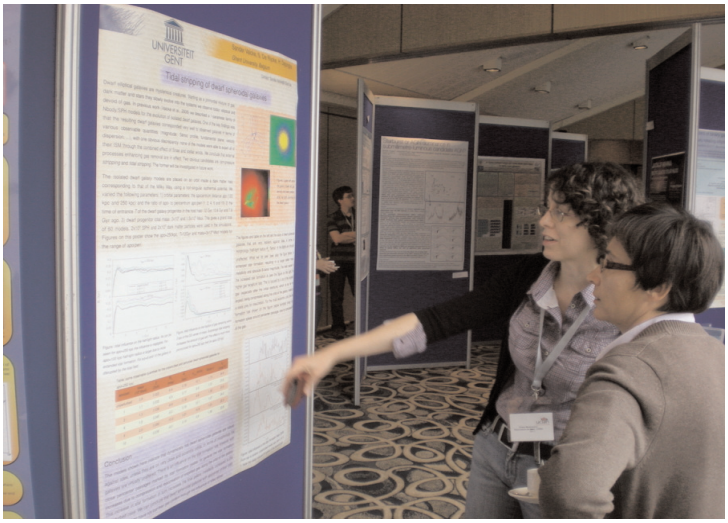

Nicholas Sammut, head of Malta Council of Science and Technology, addresses the participants during the first session.


Simon Driver describes the GAMA survey.

Participants mingling at the first break.



Pat Côté and Annette Ferguson dreaming of Canada.




Ewa Łokas and Chiara Mastropietro discuss Sander Valcke's poster.

Conference participants gathered in front of the hotel.


Aaron Romanowsky asks a question, flanked by Ellen Simmat and Joop Schaye.

Reynier Peletier and Sven De Rijcke in discussion.

Mustafa Mouchine, Daniel Pfenniger and Francoise Combes
toasting atthe banquet venue, ir-Razzett l-Antik,
a converted traditional farmhouse.

Inma Martinez-Valpuesta, Isabel Perez and Ignacio Trujillo at the banquet.

Richard Tuffs, Gordon Bromage, Cristina Popescu and Victor Debattista at the banquet hall.

Monica Valluri asks a question.

The social programme included a visit to two Neolithic temples.

Richard Tuffs and Cristina Popescu during the trip.

It was a sunny day.

Loitering outside the police station in Mdina.
Taken completely bysurprise, the police continue with their siesta.

Markus Hartmann, conference photographer and devourer of mussels (with red wine?)

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