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How, precisely, can astronomy be of benefit to anyone?

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Abstract. Astronomy as an observational science is technology driven both from the point of view of data acquisition and of data processing and visualisation. Astronomy exploits a very wide base of technologies which are developed, enhanced and extended by users. Consequently, astronomy can return new and enhanced technologies to areas well outside of astronomy itself. My own hi-tech company, Astraguard, a video imaging company, is a small but significant example of that technology return. Astronomy can provide both know-how and people for a diverse variety of areas: security, industrial process control, medical and biological imaging, petrochemicals, databases, and the financial industries to name but a few. It is unfortunate that those who teach astronomy are generally not aware of these possibilities.

In this lecture I hope to take a first step towards showing what is possible. I hope to convince the reader that astronomy education, at all levels, can play a significant role in career development outside of astronomy and in higher education in developing countries.

Keywords. Imaging, data analysis, data acquisition, statistical modelling

1. Introduction

How, precisely, can astronomy be of benefit to anyone? This is an important question in the context of modern high budget science where justification of funding in terms of goals is central to supporting one project rather than another. There is of course the purely intellectual answer that basic research is manifestly important, otherwise we, society, makes no progress. But it is hard to argue that fast spinning asteroids, however interesting they may be, are "manifestly important" to anyone other than a small community. The public, the taxpayer, feels that in these days of financial crisis there has to be a direct return on investment. Many of my academic colleagues would argue against that, saying that the return is a deeper understanding of nature from which all benefit. That may be so, but the public needs to see that benefit, it has to be tangible.

I will argue that there are many such benefits, and that astronomy is in a stronger position than most branches of science to return those benefits to the society that pays them. It is important to recognise that this public benefit is not coffee table books with lots of pretty pictures from the Hubble Space Telescope.

So how can astronomy be of general benefit to society at large? 1000 or more years ago the answer might have been: "*To make better astronomical predictions for casting more accurate horoscopes*". 500 years ago and until the last century the answer might have been "*To look after clocks and global positioning*". Today, the clearest answer might be: "*To inspire the public at large*". That is undeniably important, but surely there has to be more to it than that? There is, and my goal here is to point out what is realistically possible.

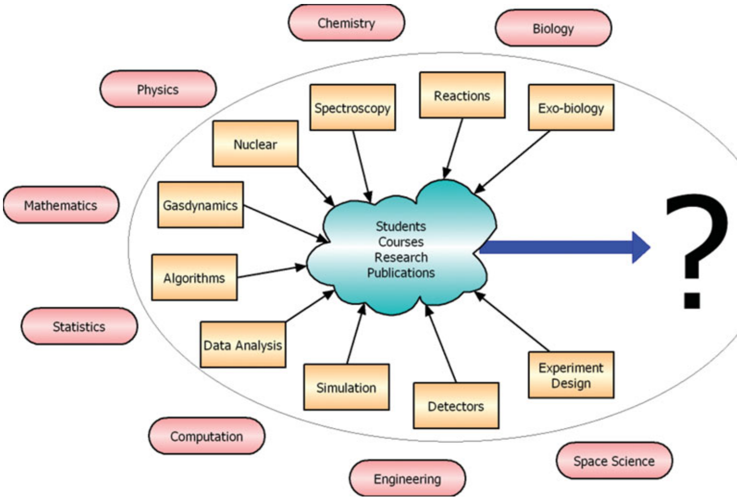

Figure 1. Disciplines learned and used by astronomers

2. Astraguard and Astronomy

Since most of this audience are not astronomers I should perhaps provide a bit of background about myself so as to explain what makes me think I might be in a position to properly address this issue. It is about 40 years since I got my Ph.D. in astronomy at Cambridge (England) under the direction of Dennis Sciama and Martin Rees, two of the greatest teachers anyone could have. I worked full time in theoretical astronomy for about 25 years at various universities around the world. In 1983, my wife Janet and I formed a hi-tech company in Copenhagen while we worked at Nordita and the Niels Bohr Institute in Copenhagen, and in 1995 I left academia to devote more time to working on my company in England. The aim of the company was to exploit knowledge gained from astronomy for the benefit of the commercial domain. We chose to focus on image and video processing: astronomers are good at dealing with images and complex data.

My company, Astraguard, specialises in video acquisition, compression, processing, analysis and storage. We sell into industrial, commercial and government markets and hope to tackle the broadcast industry. Typically, systems we sell may acquire Terabytes of data per day. These are analysed in real time (possibly many hundreds or even thousands of frames per second) for later interrogation. We can then search a month of video, perhaps a hundred million frames, for objects and events in less than one minute. Our wavelet based data compression substantially exceeds what can be achieved through the latest MPEG-4 / H.264 AVC standard both in terms of image quality and compression.

However, I continue to do cosmology and have enjoyed and still enjoy doing it in many countries. My main interest currently is to understand large scale cosmic structure using special analysis techniques. I now do and enjoy astronomy as and when I can in the group of Rien van de Weygaert in Groningen, Holland. Lots of good stuff has come from that group and you will see some of that in this presentation.

So, in short, I am qualified to discuss both astronomy and the application of astronomy outside the academic world.

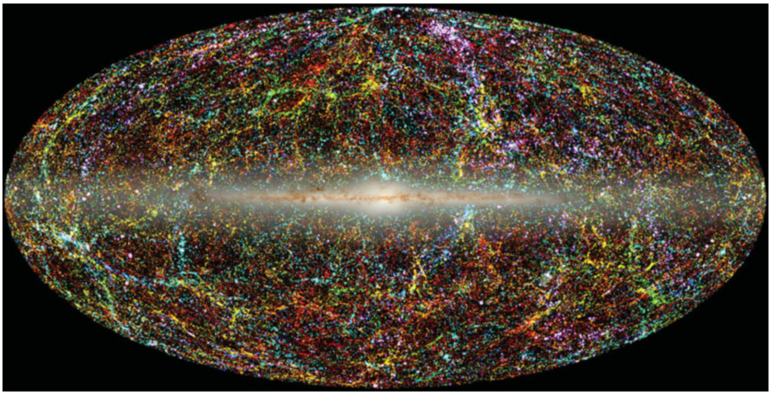

Figure 2. Panoramic view of the entire near-infrared sky reveals the distribution of galaxies beyond the Milky Way. The image is derived from the 2MASS Extended Source Catalog (XSC)–more than 1.5 million galaxies, and the Point Source Catalog (PSC)–nearly 0.5 billion Milky Way stars. The galaxies are colour coded by "redshift" obtained from the UGC, CfA, Tully NBGC, LCRS, 2dF, 6dFGS, and SDSS surveys (and from various observations compiled by the NASA Extragalactic Database), or photo- metrically deduced from the K band (2.2 μm). Blue are the nearest sources ($z < 0.01$); green are at moderate distances ($0.01 < z < 0.04$) and red are the most distant sources that 2MASS resolves ($0.04 < z < 0.1$). (Jarrett, T.H. 2004, *PASA*, 21, 396).

3. What do astronomers know about?

Astronomy as a whole involves a remarkable diversity of disciplines (see figure 1), though most astronomers tend to specialise in a subset of these and tend to stick to one area of research for most of their research lives. Research fields tend to become ever more technical and specialised.

Astronomy students get a taste of much of that diversity and will then choose to focus on things that are relevant to their supervisor's research program.

So, what are astronomers good at?

- Building instruments
- Acquiring data
- Vast databases
- Modelling data
- Simulating data
- Interpreting data

In my own field, data visualisation is becoming a key research tool. Astronomy today is very much a science of gathering large data sets, be they from ground based telescopes or from satellites, or even from numerical simulations involving billions of particles. The complexity and size of these data sets means that special techniques are required to do the presentation and analysis, and with that effort we have entered the realm of what is called "precision cosmology" † . We are no longer content with knowing the Universe started with a big bang a finite time in our past: we want to know the parameters that describe our universe as precisely as possible: we are looking for accuracy of a few percent

† You might like to take a look at IDIES, `http://idies.jhu.edu/` which is aimed at handling peta-bytes of data in what may well be one of the ultimate databases in terms of quantity of data and data access.

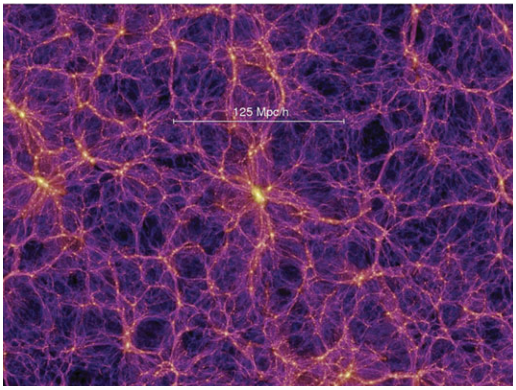

Figure 3. A slice from the vast 10 billion body "Millenium Run" simulation of the universe. This vast simulation is a source of research data in its own right. The data has been made publicly available by the authors.

or better. Modern cosmology is the interplay between data acquisition, data handling and simulation.

4. Structure in the galaxy distribution

It has long been known that cosmic structure is characterised by Clusters, Filaments, Walls and Voids: these combine together to create what is known as the "cosmic web". The structure is seen in large scale redshift surveys (Figure 2) and also in N-Body models (Figure 3). Galaxy properties appear to depend on environment and to explore that we need to accurately classify that environment. In other words, we need reproducible mathematical algorithms for identifying these elements. Later, we shall show one of these methods, *MMF*, derived from the medical imaging industry.

5. The Physics Today survey

In November 2003 the magazine / journal *Physics Today* reported on "The Business of Academic Physics". They came to several interesting conclusions:

- A physics education is a solid foundation for a diverse range of careers, but physics students do not know it. It is time they found out.
- Most academic physicists begin and end their careers in an academic setting. Thus, they have no direct knowledge about the careers that the great majority of new physicists pursue. Management needs to address this ignorance.
- In addition to adopting marketing initiatives, academic physics needs to modify its management style. Physics faculty tend to regard as physicists only those who hold a PhD in the field and are doing basic research. That narrow, self-perpetuating view is extremely counter-productive and leaves the vast majority of new physicists, at all degree levels, disenfranchised.

Table 1. Stumbling blocks

The good	The bad	The ugly
Matlab	IDL	Fortran
C++	TeX	Postscript
Excel	LaTeX	EPS
Python		
MS Word		
C♯, Java		

Their words, not mine. I am not sure that, five years on, this has changed very much. Nor am I sure that Astronomy and Astrophysics is any different.

5.1. *Some comments on that*

Maybe we should try to determine what a "solid foundation" for a career is: it may help physics/astronomy students to appreciate this.

- Not all physicists/astrophysicists live in ivory towers. The great scientific experiments of this century often bring longer term benefits to the outside world. One only has to think of microwave technology and X-Ray technology.
- Academic management styles are certainly changing, but not necessarily for the better from the point of view of the postdoc who wants a job in the outside world. The world of academic astronomy still seems geared to producing more astronomers.

In relation to the last comment, we have already heard that philosophy expounded in some of the presentations.

5.2. *Commitment to preparing graduate students for outside jobs*

I have a feeling that in astronomy and physics there is little interest in preparing graduate students for the outside world. To illustrate the point let me pose two questions that might be asked of heads of departments:

- does your department have a web page telling young people looking for higher education opportunities what they might do when they have finished their studies?
- does your department even know what happened to those students who have finished but are no longer in astronomy?

I suspect that the answer to both of these as regards astronomy is more frequently "no". That is certainly less true in engineering and in what is dubbed "applied physics", perhaps we can learn from something from them.

5.3. *Skill sets*

Employers, be they in finance, administration or technology, mostly look for individuals with "standard skills". Someone without those skills is at a disadvantage when applying for jobs. Some aspects of what we teach our graduate students are summarised in the table where I give a perhaps biased impression of the value of that learning to potential employers. Currently, most of astronomy programming is biased towards Fortran, and perhaps C. Relatively few employers use supercomputers, notable exceptions being those involved in financial modelling or the petrochemical industry,. The argument that "learning C++ to an adequate level of proficiency is easy" is entirely false. There are also issues of process threading, networking, multi-core multiprocessor architectures and

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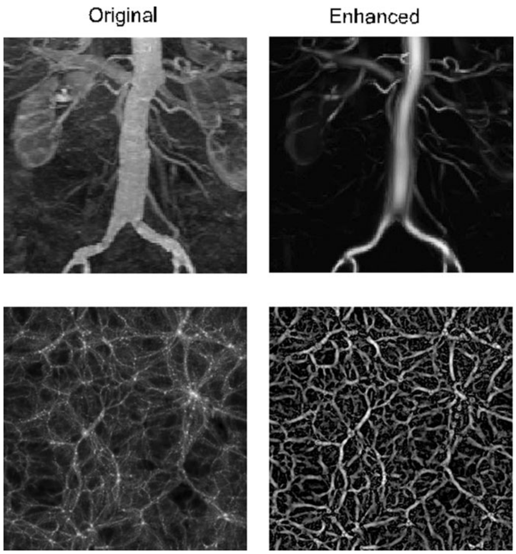


Figure 4. The top panels are from the medical industry showing the location important vessels. The lower panels are from a 2-D slice of a cosmological simulation, laying bare the filaments of the cosmic web. Note that filaments having a variety of widths are shown and that their shape is preserved.

so on. Prospective employers often give rigorous tests to candidates for their jobs and they are far from trivial. The need for Fortran skills is a comparatively small.

6. From medicine to astronomy and back

We can start with an example where astrophysics has borrowed from medical imaging and now has something to return. The distribution of galaxies in the universe is organised by the force of gravity into a "cosmic web". Some of that structure can be seen in figure 2, and it is easily appreciated in Figure 3. Astronomers wish to identify these filamentary structures, along with other structures like voids and great clusters, so that they can study the filament as an environment for galaxy formation and evolution. Isolating filaments in galaxy surveys like 2MASS and in numerical simulations allows us to appreciate how close to reality our numerical experiments are.

The van de Weygaert group in Groningen has developed an important technique for doing this called *MMF*: it derives from and extends techniques from medical imaging. The result of applying the technique is shown in figure 4. From such analysis we can localise structures and build catalogues, and so relate the galaxies to the structures that host them.

The other side of the coin is to feed back this version of the *MMF* methodology into non-astronomical areas like image and video analysis in ways that are perhaps more effective than has hitherto been achieved. That is, in part, what my hi-tech company does.

7. Data visualisation

Combining sophisticated data analysis with modern visualisation techniques presents data in a visually appealing and often striking way (see Figure 5). Some would argue that

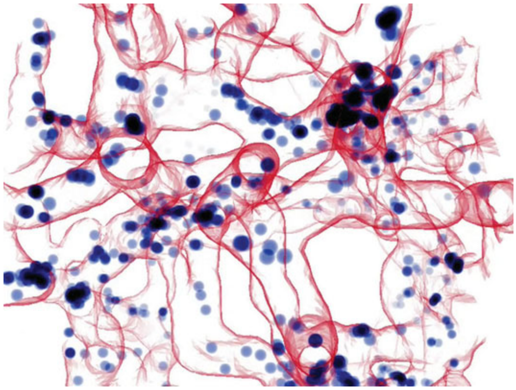


Figure 5. Visualisation of cosmic structures. Here galaxies are shown embedded in their parent filament through the use of transparency effects. The filaments in this case have been located by the SPINE algorithm. (With thanks to Miguel Aragon-Calvo for the picture which is taken from his spine movie).

such presentation of data is not "scientific", but that view is now somewhat anachronistic: it is difficult to discuss something that you cannot see, and when looking at environmental effects it is essential that the structures providing that environment be accurately delimited. Visualisation is an essential part of handling vast data sets.

Rien van de Weygaert's group in Groningen is one of the leading groups in the area of identifying and understanding these complex web-like structures. They have built their algorithms on a novel method van de Weygaert has developed, called *DTFE*, in which density fields are optimally constructed from point samples. MMF and other methods for structure finding developed in Groniingen are largely based on DTFE which is surely an important technology in its own right.

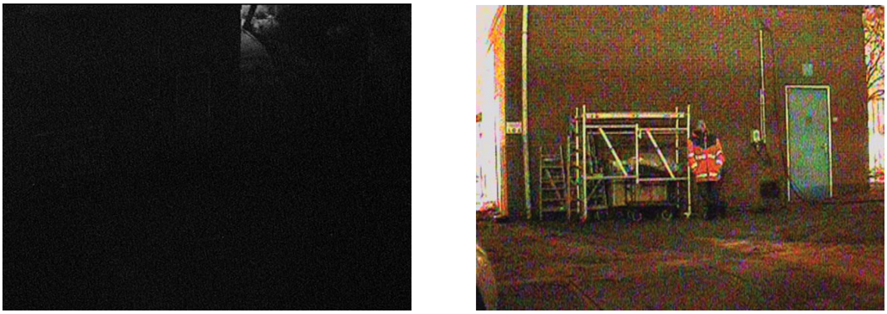
8. Detectors: CCTV and beyond

Astronomers use highly sensitive detection equipment that is able to detect individual photons of light. Nowadays these detectors are based around the CCD (Charge Coupled Device) chip that is seen in a less sensitive form in the security cameras that have become a part of our every day lives. Most security cameras used today conform to PAL, SECAM, NTSC video standards. Almost all of these cameras are CCD based and have sensitivity around 1-3 lux† in colour and 0.1 - 0.3 lux in mono.

8.1. *The Electron Multiplying CCD*

Most of these cameras have standard visual spectrum pass-band, but in the security industry there is a growth cameras covering the 0.7-1 nm waveband and corresponding LED lighting systems. There is a need for considerably greater sensitivity and to go to longer wavelengths. Thermal imaging cameras (5μm-15μm), but they require hugely expensive lenses made of solid germanium.

† One lux is equal to one lumen per square metre, where 4π lumens is the total luminous flux of a light source of one candela of luminous intensity. 10^{-5} lux is the light from Sirius, the brightest star in the night sky, 0.01 lux is the light from a quarter Moon.



(a) Regular CCTV camera 0.01 lux (b) EM-CCD detector 0.0000006 lux

Figure 6. Pictures of the same scene taken simultaneously using two cameras having different sensors. The Samsung Techwin SHC-750 that took the picture on the right is commercially available.

Enter the EMCCD (Electron Multiplying CCD) chip which is used in astronomy, and, I believe, invented at Marconi in the UK. The camera is capable of capturing pictures at night where there is little or no lighting (numbers like 10^{-5}lux or less have been quoted). Figure 6 shows what a commercial version of this device is capable of. Nothing comes for free, so whereas a typical CCTV camera retails around USD100-USD200 the SHC-750 EMCCD camera from Samsung Techwin retails at around USD5000.

9. Finance: Merton-Black-Scholes

Investors prefer safe (risk-free) investments, don't we all! An investor will buy a risky investment if he/she is convinced that the expected return on that investment will exceed what he could earn by simply putting his money in the bank. So when you want to buy, say coffee, for five years in the future you have to decide on a future price for a commodity whose price fluctuates. If the price in 5 years time is higher than you want to pay, then you would want to call the deal off. However, if the price of coffee falls too low at that time, the vendor may prefer not to sell it at a give-away price. So the deal will be struck on a compromise that a random function, the future price of your commodity, falls between two "barriers" at some specified time in the future. This sounds like a famous problem in cosmology, and it is.

Given rather specific assumptions about the way options and other financial derivatives are traded, there is a risk-free formula for evaluating how much should be paid: this is the Merton-Black-Scholes formula (1973). This formula has dominated the way in which options are traded, particularly since the equation has an exact analytic solution and so does not require a supercomputer to compute it. Indeed special hand-held calculators were built to calculate it.

This equation became so well entrenched in the financial system that prices of these financial devices were quoted in terms of the Black-Scholes Price to save traders the trouble of calculating the price! It has been argued by some that the widespread use of the formula without due regard to its limitations is perhaps a main causative factor of the present economic crisis. However, it should be remarked that there are now more sophisticated methodologies for "predicting the financial future" and so we should not blame this equation!

(a) Robert Merton (b) Myron Scholes

Figure 7. Merton and Scholes picked up the 1997 Nobel Prize for economics. Black had died earlier. Their achievement was to eliminate the risk factor that had dominated the subject before that.

9.1. *The equation*

First let us visit the financial view on how to cope with random functions. Underlying all of this is the theory of *Brownian Motion*: the study of the motion of a particle moving randomly in a fluid. The problem of Brownian Motion was first addressed by Einstein in 1905, which was one of the citations on his Nobel Prize, though it had been applied to the financial markets a few years earlier by Bachelier in his 1900 Ph.D. thesis, "The theory of speculation". The Nobel Prize winning astronomer, Chandrasekhar, wrote a seminal article on the subject in 1943.

The stock price $s(t)$ in a risk-neutral world is supposed to move according to geometric Brownian motion

$$ds(t) = r\, s(t) + s(t)\, b\, dz(t)$$

Here, b is called the *volatility* (uncertainty) of the stock price and $z(t)$ is a random function. r is the risk-free interest rate. $s(t)$ is taken to be a log-normally distributed random variable. The price, C, of the option then satisfies the equation

$$\frac{\partial C}{\partial t} + rs\frac{\partial C}{\partial s} + \frac{1}{2}q^2 s^2 \frac{\partial^2 C}{\partial s^2} = rC \tag{1}$$

The equation is linear in C and homogeneous in s. Solve this and run away with the money.

10. Barrier penetration in cosmology

Let us divert back into the realm of cosmology where it was already mentioned that there is a famous barrier crossing problem there. If

$$\Pi = \Pi(\delta, S)$$

is the probability density for the relative density excursion δ on a given smoothing scale M, where the variance of δ is

$$S = \sigma^2(M)$$

then

$$\frac{\partial \Pi}{\partial S} = \frac{1}{2}\frac{\partial^2 \Pi}{\partial \delta^2}$$

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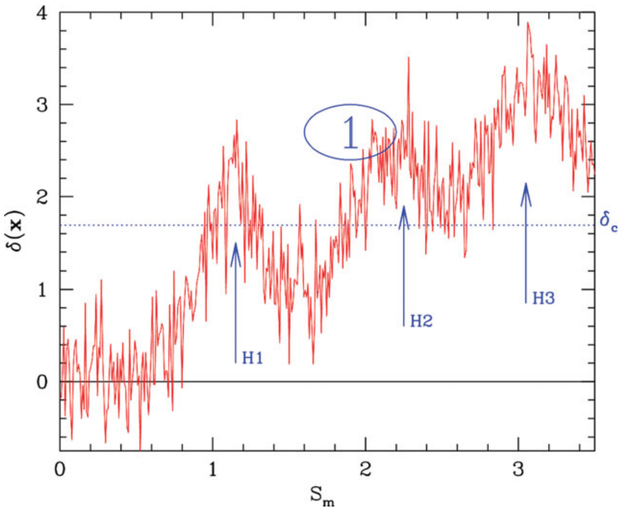

Figure 8. Variation with smoothing scale of the smoothed density contrast at a single point. δ_c is the threshold for spherical collapse. Scale H3 collapses first, to be buried later in the collapse of H2 and finally in the collapse of H1 (Sheth and van de Weygaert 2004).

The solution of this equation with appropriate boundary conditions gives the mass function of collapsed objects. This can be modified to

$$\frac{\partial \Pi}{\partial S} = \frac{1}{2}\frac{\partial^2 \Pi}{\partial \delta^2} + \beta \frac{\partial \Pi}{\partial \delta} \tag{2}$$

if the threshold is scale-dependent. The solution of this equation gives us the mass function, at each instant of time, of objects that have achieved this threshold value on some mass scale. In other words it is a model for the mass function of bound objects.

The formulation has been advanced further to handle double-barrier crossings: this enables more complex issues to be addressed and will surely have an impact beyond cosmology if someone cares to take it on.

11. What is the connection?

So, what is the link between equation (1) and equation (2)?

	Cosmology mass function		Black-Merton-Scholes
	$\frac{\partial \Pi}{\partial S} = \frac{1}{2}\frac{\partial^2 \Pi}{\partial \delta^2} + \beta \frac{\partial \Pi}{\partial \delta}$		$\frac{\partial C}{\partial t} + rs\frac{\partial C}{\partial s} + \frac{1}{2}q^2 s^2 \frac{\partial^2 C}{\partial s^2} = rC$
δ	: mass fluctuation is supposed to have zero mean and be normally distributed	s :	stock price is always positive and is assumed to be lognormally distributed.
β :	the linear growth rate of the critical threshold to form an object	r :	interest rate is assumed fixed
		q :	uncertainty assumed fixed

We shall make a change of variables

$$\delta = \ln s, \qquad K = e^{-rCt}$$

in the Black-Merton-Scholes equation. The first substitution is suggested by the statistical assumptions, and the transform of $C \to K$ is suggested by the presence of the rC term in MBS. The equation then transforms to

$$\frac{\partial K}{\partial t} + (r - \frac{1}{2}q^2)\frac{\partial K}{\partial \delta} + \frac{1}{2}q^2 \frac{\partial^2 K}{\partial \delta^2} = 0$$

which we recognise as being the cosmological equation for the mass function (we identify $S \leftrightarrow t$, $K \leftrightarrow C$, $r - \frac{1}{2}q^2 \leftrightarrow \beta$ and do some rescaling). Of course there is much more to it than that, the boundary conditions for the two problems are, for example, not the same. But the point is simply that the astrophysicist may not be unfamiliar with the mathematics of finance. The issue there may be more a lack of understanding of the technical nature of financial modelling and the associated jargon.

12. Plus ça change, plus c'est la même chose

Finally a reminder that no matter how much you discuss things and no matter what arguments you give, nothing really changes, especially for academics. This is from Plato's Republic, Book vii :

Socrates: Shall we set down astronomy among the subjects of study?
Glaucon: I think so, to know something about the seasons, the months and the years is of use for military purposes, as well as for agriculture and for navigation.
Socrates: It amuses me to see how afraid you are, lest the people should accuse you of recommending useless studies.

Socrates goes on to say that the use of astronomy is not to add to the vulgar comforts of life, but to assist in raising the mind to the contemplation of things which are to be perceived by the pure intellect alone.

Perhaps it is regrettable that is not the way things work today!

However, I do want to emphasise the point being made here. We should not train astronomers solely to produce more astronomers (a point of view mooted by some at this meeting). I do believe that most astronomers are ignorant of the large number of possibilities outside of astronomy that are open to those whom they teach. An astronomical education at all levels is rich in the variety of skills that are needed by the "outside world" today. Of course, in order to fully realise that potential, we astronomers have to change some of the things we do and to embrace more of what is needed for that outside world.

13. The bottom line

A bottom line? An astronomy education is valuable as preparation for a career in the outside world. It may be particularly important in the context of higher education in developing countries.

Acknowledgements

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