Penetration at high-z of the Greenberg ‘yellow stuff’: Eyes to the Future with NGST

David L. Block  
*Director: Cosmic Dust Laboratory, School of Computational and Applied Mathematics, University of the Witwatersrand, Johannesburg, South Africa*

Ivánio Puerari  
*Instituto Nacional de Astrofísica, Optica y Electrónica  
Calle Luis Enrique Erro 1, 72840 Tonantzintla, Puebla, México*

Marianne Takamiya  
*Department of Physics and Astronomy, University of Hawaii at Hilo  
200 Kawili Street, Hilo, HI 96720, USA*

Robert G. Abraham  
*Department of Astronomy, University of Toronto  
60 St. George Str., Toronto, ON M5S 3H8, Canada*

**Abstract.** Quantitative morphological dust-penetrated templates for galaxies in our Local Universe may also serve as excellent templates for galaxies at high-z, because of partial/total decouplings expected between gaseous and stellar disks. NGC 922 is an optical irregular, which bears a striking resemblance to objects such as HDF2-86 ($z = 0.749$) in the HDF north (Block et al. 2001). Its gaseous and stellar disk fully decouples; its stellar disk even presents modulation of spiral arms, usually only found in grand design spiral galaxies such as M81. Spiral galaxies in our Local Universe appear to be open systems, that are still forming and accreting mass, doubling their disk masses every 10 billion years (Block et al. 2002; Bournaud & Combes 2002). Likewise, galaxies at high-z may also be open systems, accreting mass, but herein NGST will provide pivotal answers. In this paper, we simulate the appearance of spiral galaxies (2–5′′ in angular diameter) with a class 6m Next Generation Space Telescope (NGST) in their dust penetrated restframe K′ (2.1μm) regime at redshifts of 0.7 and 1.2. Pitch angles, robustly derived from their Fourier spectra, remain unchanged from the present to when the Universe was roughly one half its present age. Furthermore, a ubiquity of low m (m=1 or m=2) spiral wavelets or modes is maintained in restframe K′ images at $z=0.7$ and $z=1.2$, fully consistent with K′ morphologies for spiral galaxies at $z \sim 0$ in our local Universe. This paper is dedicated to the memory of J. Mayo Greenberg, whose final research delved into dust at high-z. Nominations for the 2004 Greenberg lecture are invited.
1. Introduction

Lessons learnt from studies of objects in our Local Universe is that stellar and gaseous disks can, and do, present the most striking decouplings (e.g., Jarrett et al. 2003; Block et al. 1996, 1994; Block & Wainscoat 1991). There is no reason why such decouplings should not persist at higher redshift space. The evolved stellar disks of high-z galaxies in the HDF have never been explored at restframe K′ band. Images of galaxies with redshifts z ~ 0.5 – 1 or higher secured using the Hubble Space Telescope and NICMOS never penetrate the dusty, gaseous Population I mask. At z values greater than 3, even the H-band 1.6µm observed flux stems from emission shortward of 4000 Å. Examining HDF galaxies at restframe I (0.84µm) would not be sufficient; attenuation by dust even in the I band for some local field galaxies can still be at a level of 50 percent (Block 1996).

A poignant remark pertaining to those ‘irregular’ galaxies comprising the faint blue excess was made by Ellis (1997):

“*It is tempting to connect the rapidly evolving blue galaxies in the redshift surveys with the irregular/peculiar/merger systems ... Could this category of objects not simply be an increasing proportion of sources rendered unfamiliar by redshift or other effects? ... it is not yet clear whether the available local data samples are properly represented in all classes... the precise distinction between late-type spiral and irregular/peculiar/merger may remain uncertain.*”

In their study, Abraham et al. (1996) commented that the “shape of the faint-end number count for peculiar objects is sensitive to the large systematic uncertainties inherent in the visual classification of these objects”.

Submillimetre observations of galaxies at redshifts as large as 4 to 5 show that dust masses do not decrease with redshift: dust masses at these redshifts may still be of order 10^8 M⊙ (Norman & Braun 1996).

In this study, dedicated to J. Mayo Greenberg, we ask the question: What would the dust penetrated images of spiral galaxies at high redshift z ~ 1 look like, when the effects of dust are ‘swept away’ and when redshift as well as surface brightness dimming effects of (1+z)^−4 are fully accounted for?

The launch of the Next Generation Space Telescope (NGST) is expected during this decade. It is expected to be placed in an orbit 1.5 million kilometres away at the Lagrangian point L2, which is in line with the Sun and the Earth. The NGST science drivers dictate a class 6m size.

Imaging capabilities are expected to extend over the 0.6µm to 20µm wavelength range. Turbulence in our atmosphere distorts wavefronts passing through, leading to rapid degradation of the image. For NGST, any degradation of diffraction limited performance will only be the result of distortions in the telescope and instruments, together with pointing and tracking errors. The sky background will only be the result of scattered sunlight off, and emission from, interplanetary dust grains. The fundamental advantage of NGST for our morphological imaging purposes discussed here, will be the extremely low IR background shortward of 25µm.

In order to probe galaxies with redshifts 0.7 and 1.2 at restframe K′, imaging detectors in the broadband L (3.7µm; bandpass δL=0.65µm) and M regimes (4.7µm; δM=0.45µm) are required. At M, for example, the sky background at
an excellent groundbased site such as Mauna Kea is 10 million times brighter than it will be for NGST (see Figure 1 in Gillett & Mountain 1998, where a sky background of $\sim 305$ Jansky arcsec$^{-2}$ is indicated from Mauna Kea, but only $1.9 \times 10^{-5}$ Jansky arcsec$^{-2}$ for NGST).

Full details of the design of an $8192 \times 8192$ pixel format near-infrared camera operating on NGST from 0.6 to 5.3$\mu$m (which includes the L and M bands) may be found in Bally & Morse (1999). We follow the simulation methodology of Takamiya (1999). The simulations recreate the images of nearby $z \sim 0$ spirals when moved out to higher redshifts, always in a pre-selected restframe. Here the local spirals are simulated at redshifts $z=0.7$ and $z=1.2$ in the dust penetrated K$'$ restframe. Since the restframes are matched, no pixel $k$ correlations are applied (Takamiya 1999). Furthermore, no spectral energy distribution templates are needed: these are only required for restframes which are not matched, such as when simulating HDF restframe UV images from local $z \sim 0$ optical ones.

The angular diameters of the simulated galaxies do not scale linearly with distance but depend on the world model adopted (see Figure 2 in Baum 1972). Assuming a Friedmann-Robertson-Walker (FRW) Big Bang cosmology with a Hubble constant of 65 km/s/Mpc and a deceleration parameter $q_0$ of 0.1, the age of the Universe today is approximately 14 Gyr. The lookback times for $z$ in the interval $0.7 - 1.2$ are then about 6.0 and 7.8 Gyr. With galaxies now confirmed to almost a redshift of 6, galaxy formation ages shorter than 2 billion years must be seriously considered. Nevertheless, assuming an average epoch for galaxy formation of 2 billion years, the evolved disks of galaxies at $z \sim 0.7 - 1.2$ could lie in the 4 – 6 Gyr range. For local field spiral galaxies observed at K$'$, the ages of ‘red’ stars seen in dust penetrated images can lie anywhere from 4 Gyr and older (see the population synthesis models of Charlot et al. 1996).

Upper limits for the lookback times at $z=0.7$ and $z=1.2$ in a FRW cosmology where $q_0$ is increased to 0.5 are 5.5 and 8.2 Gyr respectively; the cosmic age decreases to 10 Gyr.

Restframe UV spectra of high $z$ galaxies are invariably dominated by young stellar populations only, although two exceptions are known. They are 53W069 and 53W091 (Windhorst et al. 2000) where Keck spectra showed that their restframe UV light was dominated by old stellar populations with apparent ages of $\sim 4.5$ Gyr at $z=1.43$ and $\sim 3.5$ Gyr at $z=1.55$.

For all our NGST simulations, we assume that the sky background is about twice the minimum background observed by COBE (Hauser 1994). We assume a sky surface brightness at L and M of 19.55 and 17.31 magnitudes per square second of arc, respectively. (From good near-infrared groundbased sites, the corresponding sky surface backgrounds at L and M are $\sim 5.99$ mag arcsec$^{-2}$ and $-0.24$ mag arcsec$^{-2}$ respectively). We furthermore assume pixel sizes of 50 milliarcseconds, a gain of 4 electrons per ADU (analog digital unit), a readout noise of 4 electrons and an output point spread function of gaussian distribution, with a full width at half maximum (FWHM) of 0.12". Assuming eight optical surfaces with 95% transmission (these include the primary and secondary mirrors as well as lenses and filters in the detector) and a 40% detector quantum efficiency, the system throughput is taken to be 26%. For all simulations, an on source integration time of one hour, was adopted.
The galaxies selected for our simulation runs, for which groundbased K′ images are available, come from a variety of groundbased sites. The telescopes used for the observations include the 3m NASA IRTF and the 2.2m atop Mauna Kea, the 2.2m at La Silla and the 2.3m at Mount Stromlo. The galaxies form part of a much larger sample of spirals used to develop our near-infrared classification scheme, and full details of each image may be found in Block et al. (2000) and references therein.

Included in Table 1 are spiral galaxies spanning the entire range of dust-penetrated classes, from α to γ. Even-sided galaxies, wherein m=2 is the dominant Fourier component, are designated by using a prefix ‘E’; lopsided, one-armed spirals (with a dominant m=1 mode) bear the ‘L’ prefix (Block & Puerari 1999). Optical arm classes of Elmegreen & Elmegreen (1987) are cited, when available, in column 4. The redshifts of the local sample are listed in column 5, determined from velocities given in the catalogue of de Vaucouleurs et al. (1991). When moved out to a cosmological distance corresponding to z=1.2, local grand design spirals such as NGC 2997 (z=0.0036) and NGC 5861 (z=0.006) only span ~ 2′′ in diameter, whereas NGC 309, the farthest galaxy in our local sample (z=0.0188) spans only 5′′ in diameter. The angular diameters of all galaxies in our simulations lie between 2′′ – 5′′.

Table 1. Spiral galaxies used in our pilot analysis. Column 2 gives the Hubble type; column 3 the dust penetrated class, column 4 the Elmegreen & Elmegreen arm classes, and column 5 the redshift

| Galaxy   | Type | Class | Arm  | Redshift |
|----------|------|-------|------|----------|
| NGC 2857 | Sc   | Eα    | 12   | 0.0162   |
| NGC 2997 | Sc   | Eβ    | 9    | 0.0036   |
| NGC 309  | Sc   | Eβ    | 9    | 0.0188   |
| NGC 3992 | SBbc | Eα    | 9    | 0.0035   |
| NGC 4622 | Sb   | Eα/Lα| 9    | 0.0145   |
| NGC 5236 | SBc  | Eα    | 9    | 0.0019   |
| NGC 5861 | Sc   | Eα    | 12   | 0.0061   |
| NGC 7083 | Sb   | Eγ    |      | 0.0102   |
| NGC 922  | Sc   | Lγ    |      | 0.0102   |

Fourier spectra were determined for each image at z=0.7 and z=1.2, and inverse Fourier transform contours were then overlaid on the simulated restframe K′ mosaics. The Fourier methodology is fully described in Kalnajs (1975) and Puerari & Dottori (1992). The Fourier spectra show a remarkable preservation of pitch angle in the dust penetrated stellar disk, as a function of redshift (see Tables 2-3). It must be stressed that the Fourier spectra are being generated on images 2′′ – 5′′ in angular size, yet the appearance of the modes are strikingly similar to those of the local z ~ 0 spectra. Dominant m=2 modes in the local sample remain dominant at z=0.7 and z=1.2 (see column 7 in Tables 2-3), where the dominant Fourier modes in the simulated images are given). In fact, given two sets of Fourier spectra, one for a galaxy at its original distance, and another, generated from the simulated image at 0.7 or 1.2, it is a challenge to find any noticeable difference in their dominant modes at all (independent of
Also extremely important is the preservation of a ubiquity of low $m$ ($m=1$ or 2) modes present at redshifts of 0.7 and 1.2 (see Figure 3) as found in local $z \sim 0$ galaxy images when viewed at $K'$ (Block & Puerari 1999; Block et al. 2000).

Our Fourier method can, we believe, be effectively used to probe and classify evolved stellar disks at these higher redshifts and may serve as an excellent morphological interface between the low and high redshift Universe.

Table 2. This table gives the pitch angle of every galaxy at its original distance in column 2. Galaxies with an ‘S’ shape have positive values for their pitch angles, while spiral arms with ‘Z’ shape have negative values. Using a 6-m NGST, columns 3 and 4 give the pitch angle in the L and M bands, respectively, assuming $q_0=0.1$. Each pitch angle is robustly determined from the Fourier spectra. Columns 5 and 6 give the values for the pitch angle at L and M for a different cosmology, wherein $q_0=0.5$. Finally, the dominant Fourier mode in each spectrum is listed in the last column. Note the excellent preservation of pitch angle in the restframe $K'$ images at $z=0.7$ (L) and $z=1.2$ (M).

| Galaxy   | L   | M   | L   | M   | M   |
|----------|-----|-----|-----|-----|-----|
| NGC2857  | -14.9 | -14.0 | -14.0 | -14.4 | -14.4 |
| NGC2997  | 25.2 | 26.5 | 25.2 | 26.5 | 26.5 |
| NGC309   | -17.7 | -17.7 | -17.7 | -17.7 | -17.7 |
| NGC3992  | 11.0 | 10.5 | 10.5 | 11.6 | 11.8 |
| NGC4622  | -4.4 | -4.5 | —   | -4.5 | -4.6 |
| NGC4622  | 8.1 | 8.7 | —   | 8.7 | 8.7 |
| NGC5236  | -11.9 | -11.6 | -11.6 | -11.6 | -11.6 |
| NGC5861  | 13.2 | 12.8 | 13.6 | 12.8 | 13.6 |
| NGC7083  | 36.0 | 33.7 | 29.7 | 33.7 | 33.7 |
| NGC922   | -38.6 | -29.7 | -29.7 | -38.6 | -33.7 |

For local field galaxies, Block & Puerari (1999) find a duality of spiral structure. One classification for the Population I disk; often a radically different one for the Population II disk. There is no reason why this kinematical distinction should not be equally applicable to spiral galaxies at redshifts of approximately 1. The fundamental rather than incidental need to develop a near-infrared classification scheme is kinematically driven; 95 percent of the mass distribution remains unprobed in the optical mask. NGST will clearly cause a renaissance in identifying such dualities for galaxies at high redshift.

The need for an NGST larger than 4m is compelling for morphological studies of stellar disks. A comparative performance between a 4m NGST and 8m NGST is evident in the simulations. Note the appearance of missing entries in Table 4 compared to Table 2. Our simulations always assume diffraction limited images and furthermore, that the pixel sizes are such that the point spread function is critically sampled. Clearly for a 4m NGST the sampling in arcseconds is worse than for a class 8m NGST, and the pitch angles for some of the arms, measurable with an 8m NGST, are no longer measurable with a class 4m NGST. For those galaxies with a missing entry in Table 4, the arms have
Figure 1. NGC 5861. Upper left: The original groundbased K’ image. Upper right: Contours determined from the inverse Fourier transform are overlayed on the groundbased K’ image. Middle left: A simulated image of NGC 5861 with an 8-m NGST at a redshift z=0.7 (L band). Middle right: The L band image, with contours (determined from the inverse Fourier transform) overlayed. Bottom left and right show the galaxy redshifted to z=1.2 (M band) with and without contours. For simulations illustrated here, a value of q0=0.1 is assumed. Notice the remarkable preservation of pitch angle with increasing redshift. Also notice the power of the Fourier method to delineate spiral arms at z=1.2.
Figure 2. NGC 922. An optical irregular/peculiar; a possible local prototype of many higher redshift ‘irregulars’. Upper left: The original ground-based K′ image shows a strikingly different morphology – even with arm modulation (Fig 3), usually only found in grand design spirals such as M81. Upper right: Contours determined from the inverse Fourier transform are overlayed on the ground-based K′ image. Middle left: A simulated image of NGC 5861 with an 8-m NGST at a redshift z=0.7 (L band). Middle right: The L band image, with contours (determined from the inverse Fourier transform) overlayed. Bottom left and right show the galaxy redshifted to z=1.2 (M band) with and without contours. For simulations illustrated here, a value of q₀=0.1 is assumed. Notice the remarkable preservation of pitch angle with increasing redshift. Also notice the power of the Fourier method to delineate spiral arms at z=1.2.
Figure 3. Fourier spectra may easily be generated on post-stamp images only 1-2 arcminutes on a side. The Fourier spectra of the K' image of NGC 922 at its unredshifted distance is shown at top. The middle row shows the Fourier spectra when the galaxy is moved to redshifts $z=0.7$ (L band) and $z=1.2$ (M band), respectively and a class 6m NGST. A deceleration parameter of $q_0=0.1$ is assumed. The bottom row shows the Fourier spectra for the same redshifts values, but assuming a different cosmology with $q_0=0.5$. Notice that while there are small changes in the shape of some of the modes such as $m=1$, pitch angles determined from the dominant $m=2$ Fourier mode are almost identical.
Figure 4. The template above classifies stellar disks in our Local Universe according to three dust penetrated arm classes ($\alpha$, $\beta$ and $\gamma$), linked to rotation curve shapes and rates of shear. The second parameter is the gravitational torque of the disk. NGC 922, which might well serve as a local Rosetta stone for morphologically peculiar systems in our higher redshift universe, has a gravitational torque of two, in a range from 0-7, and is of class $\gamma$. 
As in Table 2, but for a class 8m- NGST

| NGC2857  | -14.9 | -14.9 | -13.6 | -14.4 | -14.4 (m=2) |
|----------|-------|-------|-------|-------|-------------|
| NGC2997  | 25.2  | 26.5  | 28.0  | 26.5  | 26.5 (m=2)  |
| NGC309   | -17.7 | -17.7 | -17.7 | -17.7 | -17.7 (m=2) |
| NGC3992  | 11.0  | 11.3  | 11.0  | 10.8  | 11.8 (m=2)  |
| NGC4622  | -4.4  | -4.5  | -4.5  | -4.5  | -4.5 (m=1)  |
| NGC4622  | 8.1   | 8.4   | 8.6   | 8.4   | 8.4 (m=2)   |
| NGC5236  | -11.9 | -11.9 | -11.9 | -11.9 | -11.9 (m=2) |
| NGC5861  | 13.2  | 14.0  | 13.2  | 13.2  | 13.2 (m=2)  |
| NGC7083  | 36.0  | 33.7  | 31.6  | 36.0  | 33.7 (m=2)  |
| NGC922   | -38.6 | -38.6 | -45.0 | -33.7 | -38.6 (m=1) |

become blended into the disk in the simulated 4m NGST image and cannot be unambiguously traced.

We have also run a series of simulations using ground-based class 8m telescopes equipped with L and M detectors. Due to the huge factor of $\sim 10^7$ Jansky arcsec$^{-2}$ corresponding to a $\sim 17.5$ magnitude arcsec$^{-2}$ increase of the M sky background, at a redshift of 1.2 no spiral structure can be seen in any of the M band images. Thermal emission from molecules in our lower atmosphere and from the ambient temperature of the telescope itself dominate the dark sky background longward of 2.3 $\mu$m at ground-based sites. Herein lies the great benefit of NGST. NGST is expected to be passively cooled to a temperature of $\sim 30$ K thus minimising a contribution from the telescope itself, and of the instruments, to an unprecedented dark sky background.

2. Eyes to the Future: A Tribute to J. Mayo Greenberg, by DLB

Probably the final topic which received much attention by the late Professor J. Mayo Greenberg was the subject of dust in the high-redshift universe: hence the dedication of this research report to him.

Allow one of us (DLB) some personal reflections:

When I first decided to nominate Mayo for the Henry Norris Russell prize in 1997, letters in support of my nomination were received by Professors L. Spitzer (Princeton University Observatory), H. vd Hulst, G. Miley and E. van Dishoeck (at Leiden), R.J. Allen (Baltimore), Bruce and Debbie Elmegreen (NY), D.A. Williams (University College London), P. Hodge (Editor of the *Astronomical Journal* in Seattle) and L. Allamandola, D. Cruikshank and Y. Pendleton (NASA-Ames). The letters bore stature of the greatness of the man. Sadly, both Lyman Spitzer and Henk vd Hulst passed on, shortly after they wrote their recommendation letters.

As fundamental as the Hertzsprung-Russell diagram is to our understanding of stellar evolution, so pivotal was the pioneering insight of Mayo Greenberg to our understanding of the chemical composition and evolution of dust grains in our Galaxy, and beyond.
The bond Mayo and I shared was exceptionally close. Mayo taught me to always look up. He always encouraged me. He once wrote this note in my copy of his book *Evoluzione della polvere interstellare e questioni attinenti* (International School of Physics: Enrico Fermi; Evolution of Interstellar Dust and Related Topics).

Figure 5.
Figure 6. Mayo Greenberg photographed in South Africa with Mr Michael O’Dowd, then Chairman of the Anglo American and de Beers Chairman’s Fund. In the background is Professor James Lequeux, with the author at right.

The field in which Mayo played such an absolutely pioneering, leading role over the decades is now turning out to be one of the most rapidly developing areas in galactic and extragalactic astrophysics.

Not surprising. The distribution of dust tends to delineate the location of the material for future generations of stars and offers evidence of a history of past stellar processing of the ISM and metal enrichment.

As was recognised at our international conference on galaxy morphology and cold dust held at our University in January 1996 (attended by over 100 astronomers worldwide), the predictive powers of Mayo’s work were absolutely remarkable. Remarkable both in depth, and in originality.

He did not develop theories to explain existing observations; rather, Mayo developed models and predicted scores of observations.

Conditions simulated by Professor Greenberg for the study of the photo-chemistry of low temperature ices related to the photoprocessing of interstellar dust opened up fundamentally new paths: all of the chemical work that was done on molecules in giant molecular clouds prior to that assumed ion molecule chemistry, absolutely ignoring the fact that there was dust there. Researchers had ignored it from so many points of view, it would be impossible for me to enumerate them.

Greenberg’s far-reaching insights into the pivotal role which the evolution of dust grains play in our understanding of star formation, are only now being fully appreciated. His now famous silicate core/organic refractory and ice mantle model for dust grains was developed decades before the advent of modern ground and space based instruments could test the models.
Figure 7. Ready for a game drive in South Africa. Enjoying Life (capital L emphasized) to the utmost, is Mayo, seated in front of this 4×4. Seated behind Mayo is (L-R) his wife Naomi; Liz & Aaron Block, and Michelle Griffiths. In the back row are Ana-Maria Macchetto and Professor Richard Griffiths. Standing next to the 4×4 is Duccio Macchetto, Science Director at STSCI, while a game ranger keeps guard from the rear of the vehicle.
Figure 8. Mayo Greenberg in Pretoria, South Africa, standing on the steps of the Voortrekker Monument. A contrast in profiles: one in stone, the other in flesh. ‘Voor’ = front in Afrikaans; ‘trekker’ = ‘traveller’. Photograph by the author.
I think in particular, of the confirmation from spectroscopic studies of the silicate spectral features at $9.7\mu m$ and $18\mu m$ and the $3.4\mu m$ organic feature in the diffuse interstellar medium.

But there is more. Dust is swept by stellar winds and explosions into clumps, clouds, shells, and filaments that can collapse to give rise to new stars. Such structure also mitigates the radiative transfer in a galaxy, shielding star forming clouds from photodissociation, or in its absence, leaving clouds mostly dissociated, as dense molecular cores inside large warm atomic shells. Greenberg was the first to predict, almost 30 years ago, the ‘temperature fluctuations’ or ‘temperature spiking’ of very small dust grains. Again the master’s vision has been soundly confirmed both by further theoretical and observational studies.

There is more. Cold ($20K$ and colder) dust grains, acting as a cosmic mask or fog, may obscure a huge $\sim 95\%$ mass fraction of Pop II galactic backbones. Significant dust content can play havoc with attempts to accurately measure the light and color distributions in a galaxy, especially if it is embedded as opposed to a foreground screen. Moreover, dust can play havoc with inferences for the morphological classification of stellar Population II disks from gaseous Population I speciations, on which the Hubble tuning fork is based. A entirely new near-infrared classification scheme emerges when galaxies are mask penetrated; the Hubble tuning fork strikes a new note.

Greenberg was right on target. Over three decades ago, he predicted that 80-90 percent of the dust mass in a galaxy would consist of cold and very cold grains (see his pioneering paper ‘Interstellar grains and spiral structure’ in the 1970 volume edited by H. Habing) and therefore undetected by IRAS. It is
Figure 10. Surrounded by his ever favourite ‘yellow stuff’ in this caricature (by Cliff Brown) is Mayo Greenberg. All rights reserved.
Figure 11. Mayo Greenberg in Africa. (Top) with Matthias Steinmetz (left), Rogier Windhorst and B. Rocca-Volmerange. Photograph by Cliff Brown. (Bottom) On a tour visiting Soweto. Photograph courtesy Liz Block.
Figure 12. Mayo had predicted the existence of 20K cold cosmic dust in our Galaxy, and beyond, decades ago. The observational challenge then was to find those grains which IRAS did not detect in galaxies outside of our own. Mayo handed this note to our team of researchers at a Conference in Cardiff in 1994: "I've been waiting 23 years to 'see' cold dust. You did it. Thanks! Mayo." A greater mentor cannot be envisaged.

Figure 13. Mayo’s ‘office’ knew no bounds. A few quick calculations (handwritten by Mayo in a hotel room in South Africa) appear on a Keck NIR spectrum of the brown dwarf Gliese 229B, published by B. R. Oppenheimer et al. in 1998. The words ‘Oppenheimer et al.’ appear, in Mayo’s writing, at top left. Mayo – a man, heading for 80, with an unprecedented sweep and appreciation of current literature.
precisely these ‘large’ (tenth micron) grains which are responsible for the visual extinction in galaxies; not the smaller, one-hundredth micron grains.

In January 1996, we could all salute the legendary Greenberg on the fact that optical minus near infrared imaging combined with radiative transfer codes, now beautifully confirmed his predictions: dust masses (and therefore dust-gas ratios) can increase by one order of magnitude. Interarm dust is everywhere. [See the volume which Mayo and I edited, entitled ‘New Extragalactic Perspectives in the New South Africa’, Kluwer, 1996].

Greenberg’s predictions were made some 30 years before 2D direct imaging could routinely become possible longward of I (0.89 \( \mu m \)). Sub-millimetre/mm observations had brought the issue of cold dust to the fore, but with controversial and diametrically opposed conclusions. Quantitative techniques to probe the full spatial extent of dust grains of all temperatures awaited the commissioning (circa 1990) of large format HgCdTe NICMOS arrays on telescopes at Mauna Kea and elsewhere. We generated optical minus near-infrared colour maps to establish the existence, at arcsecond resolution, of a cold and very cold population of (interarm) dust, and Greenberg’s predictions were conclusively verified in 1994 and 1996.

As I reflect over the publication list of Greenberg, I must, in passing, salute the master in a paper co-authored by him in Nature, concerning the possibility of dust grains in in galactic haloes. 4096×4096 pixel CCD imaging of the galaxy NGC5907 with the Canada France Hawaii Telescope suggests – on observational grounds – that dust may be present in its halo. Colour excesses are at levels of \( \sim 0.1 \) magnitude for the halo NGC 5907, comparable to interarm colour excesses one finds in dusty galactic disks (eg. NGC4736). While it remains a great observational challenge to image galactic haloes, Greenberg blazed the theoretical trail.

Greenberg predicted

• that the nucleus of Comet Halley would be black (Nature, 321, 385, 1986)
• that the cometary dust would be \( \sim \) one half rocky-silicate, the rest being in the form of complex organic material.

On both counts Greenberg was right again: predictions confirmed by the Vega 1, Vega 2 and Giotto missions.

I have only referred to a handful of the implications of the 300+ papers authored by Greenberg. In the citation survey conducted by P.C. van der Kruit entitled ‘Astronomical Community in the Netherlands’ [published in the Quarterly Journal of the Royal Astronomical Society (vol. 35. no. 4, pg 421, 1994)], Professor Greenberg held the highest number of cited publications of any astronomer in the Netherlands for the year 1991. No mean achievement for a researcher then at age 70! We indeed stand on the shoulders on giants.

Thus far, I have only focussed on some of the publications of Greenberg. I have not alluded to the doctoral students Professor Greenberg has mentored; scientists such as L. d’Hendecourt who are now, in their master’s footsteps, playing crucial roles in our understandings of, for example, polycyclic aromatic hydrocarbons. Neither have I alluded to students who have worked with Greenberg in a postdoctoral capacity, and who later went on to establish research groups of the highest calibre. I think of Lou Allamandola, for example, who worked as a postdoc in Greenberg’s Laboratory at Leiden.
What a fitting way it was to salute the man in 1997, when I invited astronomers from around the globe to send in their birthday wishes to Mayo on his 75th birthday. Scores, dozens, of emails, poured in. George Miley wrote the first congratulatory email:

“Your presence during the last two decades has been of immense benefit to the prestige of Leiden. Your immense enthusiasm and stimulating attitude to research is a joy to see. I cannot believe that you are three quarters of a century young. I regard it as a great privilege to have you as a colleague and friend. On behalf of Hanneke and myself, Happy Birthday!”

Next followed an email to my office from Sir Martin Rees, Astronomer Royal. This message was followed by emails from Ron Allen, the Elmegreens, Y. Terzian, G. Herbig, B. Draine, A. Li, F. Israel, J. Mather, and about 100 more researchers.

Walt Duley (University of Waterloo) pleaded:

“Happy 75th, Mayo! Please don’t answer ALL the outstanding questions on dust before you retire. Leave a few for the rest of us to deal with! Your friend, Walt Duley.”

Mayo always remembered his viewing of Comet Halley at the home of Bruce and Debbie Elmegreen. Bruce recalled:

“...you never failed to impress me with the breadth and originality of your work. I also have the fondest memories of viewing Halley’s comet with you in our back yard. I wish you and your family many many more happy years. Bruce Elmegreen.”

George Herbig, in his congratulatory email, included a small, but precise, calculation:

“Dear Mayo: May your life continue to be filled with dust, molecules, and other assorted interstellar debris! Best regards and congratulations on passing the $2.366 \times 10^9$ s milestone, George Herbig.”

Kalevi Mattila recalls:

“Your visits to Finland and your presentations are well remembered still today – not least the magic tricks you presented to my (at that time) small children. The first international meeting I attended – the interstellar dust conference in Jena in 1969, was organized under your leadership. Ever since then it has always been a great pleasure and inspiration for me meeting you at different places and conferences…”

Martin Cohen (Berkeley) summed it up well:

“That yellow soup obviously agrees with you!”

From founding the microwave scattering laboratory at the Rensselaer Polytechnic Institute in New York, to the Laboratory of Astrophysics in Leiden, we continued to see a man not only characterized by a lifetime of trailblazing research, but there was more. Like his beloved hero Einstein, Mayo was, in his chosen field, a giant of a man whose profound predictive theoretical insights were truly astounding. As Professor John Kerridge (UCSD) emphasized:

“You have left an indelible and constructive mark in a host of fields, but of course most notably in the relationships between interstellar grains, comets, and primitive solar systems. Like so many others, I have learnt a great deal from your numerous studies in that area…”
Mayo was a family man, and Naomi was his closest earthly companion. The love they shared – how they still held hands whilst briskly walking the streets of Leiden – are especially etched in my mind. For me to be included in his innermost circle of galactic research companions was an immense privilege. When I first met Mayo, it seemed as if we had known one another for years. There was a mutual bond – a tie of extraordinary friendship (Figure 5).

The Greenberg home on the Rhine... the hospitality which Naomi and Mayo extended to my wife Liz and me at Morsweg over the years can, and will, never be forgotten. Taxis were ‘forbidden’. On my last arrival at Schipol Airport, to speak at the Oort Centenary, Mayo and Naomi were both there to meet me. To quote George Miley: their hospitality was legendary.

Mayo had an exuberance for Life – with a capital L. He loved to LIVE. He loved to encourage. He visited me in South Africa on two occasions (figures 6-11), and we also walked the streets of Paris. We visited the Musée Rodin together. He marvelled at Camille Claudel’s onyx and bronze La Vague and at Rodin’s The Walking Man, The Eternal Idol, La Tour du Travail and many others. Each visit by him was filled with enough dreams to last for a lifetime.

When we went game viewing in our South African reserves, Mayo was always there – right in the front seat of the 4×4. His eye, always eager to spot a lion kill; a herd of elephant; a stalking cheetah.... At meal time, Mayo kept all enthralled. I recall staying at his home about a year or two before he passed away ... and to see a man, close to 80, carrying his back-pack, rushing off to catch the train (en route to the airport) to yet another Conference abroad, left an indelible impression on me.

There is a lot I will not say, because they are personal memories. But let me say this: Mayo enriched my life. He encouraged me, never to give up. He supported every facet of my research. Figure 12 shows but one example. We probably spoke on the telephone at least twice a month – often much more. If not by phone, we constantly emailed one another. We thoroughly enjoyed chatting about a huge range of topics, including the magnificent near-infrared spectra of the brown dwarf Gliese229B by Tom Geballe, B.R. Oppenheimer, S.R. Kulkarni and their collaborators (Figure 13).

I had already partly constituted a Scientific Organising Committee to organise a Conference here in South Africa for Mayo’s 80th; much support was received from George Miley, Francoise Combes, Johan Knapen, Duccio Macchetto, Bruce Elmegreen and Ken Freeman, among others. But it was not to be. Fortunately George Miley, Ewine van Dishoeck and Willem Schutte were able to quickly organise a meeting in Mayo’s honour, in Leiden; Mayo was physically still strong enough to attend.

I spoke to Mayo in his hospital bed in Belgium. We spoke just before he passed on, at his home in Morsweg. He was almost too weak to speak. But there came the voice, weak but still speaking of future research plans and about dust in the high redshift universe.

That is the impetus of the work presented here: to explore the efficiency and possibility of penetrating masks of cosmic dust at high-z, with NGST.

Mayo was one of my very closest research companions, and we miss him sorely.
**2004 Greenberg Memorial Public Lecture**

In 2004, we plan to fly out a researcher from abroad to South Africa, to deliver a public lecture at our University Great Hall (seating capacity, 1000 persons) in honour of J. Mayo Greenberg. The lecture will probably coincide with our International Conference *Penetrating masks of Cosmic Dust: The Life Duty Cycle of Bars* which takes place in June 2004. Mayo would indeed have returned to South Africa, but his health declined so fast. In was in South Africa that Mayo met the Cabinet Minister for Arts, Culture, Science and Technology, Dr Ben Ngubane (see figure 9). Dr Ngubane is intimately involved with the 10-m Southern African Large Telescope SALT being constructed in South Africa.

The lecturer need not have personally have worked with Professor Greenberg, but the theme of the lecture must obviously be one close to one of Greenberg’s passions – whether it be comets, extrasolar systems, the dusty ISM, or the dusty high redshift universe. Interested persons are invited to email one of the authors (at block@cam.wits.ac.za) for further information: it is anticipated that one international airfare and local accommodation will be fully paid for.

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Acknowledgments

DLB expresses his deepest thanks to Ivánio Puerari, Marianne Takamiya 
and Bob Abraham, his collaborators on this NGST 922 restframe K-band sim-
ulation project.

DLB is indebted to the Anglo American Chairman’s Fund and to Clem 
Sunter, M. Keeton, Hugh Rix and the Board of Trustees. This research was 
also supported by SASOL; a warm note of gratitude to Chairman Mr P. Kruger 
and to the SASOL Board.

DLB thanks E. van Dishoeck and W. Schutte for the opportunity to write 
his reflections on JMG in their forthcoming publication, too. He is most indebted 
 to George Miley for keeping him fully abreast (both by telephone and email) of 
all developments, as Mayo’s days neared their end.

DLB recalls Mayo’s great excitement at attending Yvonne Pendleton’s star-
dust and planetesimals conference in California (subsequently published in 
the ASP Conference Series), and for the purposes of releasing this paper on 
the WWW, we have compiled this paper using the Latex stylefile of the Astronom-
ical Society of the Pacific. The actual stylefile to be used will be decided upon 
by the 2004 Cosmic Dust/Bar Conference editors Ken Freeman, David Block, 
Ivánio Puerari and Robert Groess.
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