January 17, 2008

Dr. M. Arnaud
Orme des Merisiers - Bat 709
Service d'Astrophysique
Gif sur Yvette, F-91191
France

Dear Dr. Arnaud:

Please accept the attached application for your postdoctoral position in X-ray astronomy advertised in the January 2007 issue of the AAS Job Register. For my thesis (advised by Megan Donahue and Mark Voit), entitled *'Feedback, Evolution, and Dynamics in Galaxy Clusters'*, I am studying the coupling of feedback mechanisms – such as AGN, star formation, and conduction in cluster cores – to gas entropy, and the role of this feedback in altering global ICM properties and truncating the high mass end of the galaxy luminosity function. I have also been studying a method for quantifying the virialization state of clusters through the band dependence of X-ray temperatures. For my thesis I assembled a sample of 350 archival *Chandra* observations for 276 clusters totaling 11.6 Msec of data. The results of this laborious effort have been many and are detailed in my research summary.

I feel the post-doctoral position under your advisory at SAp is an excellent fit for me, and your research goals will benefit from my addition. My expertise in X-ray astronomy ideally suits me to further study the evolution of galaxy clusters and mass-observable relations as tools for conducting tests of cosmological models and toward a better understanding of the cluster mass distribution as a function of redshift. Adaptation of my skill sets to study clusters in the radio, optical, and infrared is the next step in my career and should come with a short learning curve thanks to my existing, mature programming ability.

Along with this letter are my CV, a list of publications, a summary of past and current research, and a brief description of possible research directions. Letters of recommendation from Megan Donahue, Mark Voit, and Jack Baldwin should already have arrived under separate cover. Please do not hesitate to contact me if there is any further information I can provide as you review my application.

Thank you for your consideration.

Sincerely,

Kenneth W. Cavagnolo
Michigan State University

Kenneth W. Cavagnolo
Curriculum Vitae

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Michigan State University
Department of Physics & Astronomy
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Education

Michigan State University 2005 - Present
Ph.D. Astrophysics, Expected August 2008
Thesis Title: “Virialization, Entropy, & Feedback in Clusters of Galaxies”
Advisors: Dr. Megan Donahue & Dr. G. Mark Voit

Michigan State University 2002 - 2005
M.S. Astrophysics, *Magna Cum Laude*
Dissertation Title: “Entropy Profiles of Cooling Flow Clusters”
Advisor: Dr. Megan Donahue

Georgia Institute of Technology 1998 - 2002
B.S. Physics, *Magna Cum Laude*
Senior Thesis: “Analysis of the Eclipsing Binary ET Tau”
Advisor: Dr. James Sowell

Research Experience

Graduate Research Assistant 2003 - Present
Supervisor: Dr. Megan Donahue, *Mich. St. Univ.*
Studying clusters of galaxies via their X-ray properties to investigate feedback mechanisms, galaxy evolution, and the process of cluster virialization.

Graduate Research Assistant 2002 - 2003
Supervisor: Dr. Jack Baldwin, *Mich. St. Univ.*
Analyzing echelle spectra for use in studies of *s*-process abundances in planetary nebulae.

Undergraduate Research Assistant 2000 - 2002
Supervisor: Dr. James Sowell, *Georgia Tech*
Obtaining orbital solution for the eclipsing Algol binary ET Tau via UBV light curves and spectroscopic radial velocity curves.

Research Interests

- Large Scale Structure Formation and Cosmology
- Galaxy Cluster Evolution
- Feedback Mechanisms in Galaxy Clusters
- Sunyaev-Zel’dovich Effect
- Galaxy Formation

Teaching Experience

Substitute Instructor — Fall 2006
Course: "Visions of the Universe"
Gave lectures covering stellar evolution, supernovae, white dwarves, neutron stars, and black holes.

Physics Tutor — Summer 2003
Course: "Introductory Honors Physics I & II"
Tutored physics students taking introductory physics courses such as classical mechanics, optics, and electromagnetism.

Graduate Teaching Assistant — 2002 - 2003
Course: "Visions of the Universe"
Directed and supervised laboratories for non-calculus based astronomy course.

Honors

- MSU College of Natural Science Dissertation Fellow — 2007 - Present
- American Astronomical Society Member — 2002 - Present
- American Physical Society Member — 2002 - Present
- Sigma Pi Sigma National Honor Society — 2001 - Present
- Dean's List, Georgia Tech — 1998-2002

Scientific Skills

- Profound skills in reducing and analyzing data taken with *Chandra* X-ray Telescope.
- Extensive experience with customizing and debugging CIAO and CALDB.
- Familiarity with multiwavelength analysis packages: AIPS, IRAF, and PyRAF.
- Fluent in PERL, IDL, LaTeX and HTML.
- Working knowledge of C, Flash, Fortran, MySql, SuperMongo, and Tcl.
- Mastery of multiple computing architectures: DOS, Linux, Macintosh, and Windows.
- Expert of computer troubleshooting, maintenance, and system construction.

References

Dr. Megan Donahue
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Michigan State University

Dr. G. Mark Voit
(517)-355-9200 ext. 2419
voit@pa.msu.edu
Michigan State University

Dr. Jack Baldwin
(517)-355-9200 ext. 2411
baldwin@pa.msu.edu
Michigan State University

Personal Interests

- Academic: environmental sciences, "Cradle2Cradle" design, and urban planning.
- Athletics: triathlons, baseball, and everything Georgia Tech.
- Hobbies: reading, building model airplanes, and raising bonsai trees.

KENNETH W. CAVAGNOLO
PUBLICATIONS

First Author Refereed Papers

"X-ray and Entropy Scaling Relations in Galaxy Clusters"
Cavagnolo, Kenneth W.; Voit, G. Mark; and Donahue, Megan
2008, in prep. for ApJ

"Feedback Mechanisms in Galaxy Clusters and Alteration of ICM Entropy"
Cavagnolo, Kenneth W.; Donahue, Megan; and Voit, G. Mark
2008, in prep. for ApJ

"Star Formation in BCGs: Resurrecting Conduction"
Cavagnolo, Kenneth W.; Donahue, Megan; and Voit, G. Mark
2008, in prep. for ApJL

"Athenaeum of Galaxy Cluster Entropy Profiles"
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2007, near ApJS submission

"X-ray Band Dependence of X-ray Temperatures in Galaxy Clusters"
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2007, ApJ submitted

Other Refereed Papers

"Star Formation, Radio Sources, Cooling X-Ray Gas and Galaxy Interactions in the Brightest Cluster Galaxy in 2A0335+096"
Donahue, Megan; Sun, Ming; O'Dea, Christopher P.; Voit, G. Mark; **Cavagnolo, Kenneth W.**
2007AJ....134...14D

"Entropy Profiles in the Cores of Cooling Flow Clusters of Galaxies"
Donahue, Megan; Horner, Donald J.; **Cavagnolo, Kenneth W.**; Voit, G. Mark
2006ApJ...643..730D

"s-Process Abundances in Planetary Nebulae"
Sharpee, Brian; Zhang, Yong; Williams, Robert; Pellegrini, Eric; **Cavagnolo, Kenneth**; Baldwin, Jack A.; Phillips, Mark; Liu, Xiao-Wei
2007ApJ...659.1265S

Presented Work & Talks

INVITED TALK: *"The Effect of Cluster Feedback on High-Precision Cosmology"*
Feb. 2008 – NASA National Space Science and Technology Center, UAH-Huntsville

INVITED TALK: *"Understanding Feedback in Galaxy Clusters"*
Jan. 2008 – Center for Study of Cosmic Evolution Seminar, Michigan State University

INVITED TALK: *"Band Dependence of X-ray Temperatures"*
Oct. 2007 – University of Michigan Astrophysics Seminar

POSTER: *"The Entropy-Feedback Connection and Quantifying Cluster Virialization"*
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2007 Eight Years of Science with Chandra Symposium

POSTER: *"Chandra Studies of Dark Matter and Galaxy Formation: Signatures from the Intracluster Medium"*
Donahue, Megan; Sun, M.; **Cavagnolo, K.**; Voit, G.
2006 Winter Meeting of the American Astronomical Society

PROCEEDING: *"Abundances of s-process elements in planetary nebulae: Br, Kr & Xe"*
Zhang, Y.; Williams, R.; Pellegrini, E.; **Cavagnolo, K.**; Baldwin, J. A.; Sharpee, B.; Phillips, M.; Liu, X.-W.
2006 IAU Symposium

POSTER: *"Studies of Entropy Distributions in X-ray Luminous Clusters of Galaxies"*
Cavagnolo, K. W.; Donahue, M. E.; Voit, G. M.; Sun, M.; Evrard, A. E.
2005 Winter Meeting of the American Astronomical Society

POSTER: *"Entropy Distributions in the Cores of Nearby X-ray Luminous Clusters of Galaxies"*
Cavagnolo, K. W.; Donahue, M. E.; Voit, G. M.; Horner, D. J.; Evrard, A. E.
2004 Winter Meeting of the American Astronomical Society

POSTER: *"Radio-Free Cluster Cooling Flows"*
Donahue, M. E.; Voit, G. M.; **Cavagnolo, K.**
2004 Winter Meeting of the American Astronomical Society

Summary of Experience and Future Interests

The general process of galaxy cluster formation through hierarchical merging is well understood, but many details, such as the impact of feedback sources on the cluster environment and radiative cooling in the cluster core, are not. My thesis research has focused on studying these details via X-ray properties of the ICM in clusters of galaxies. I have paid particular attention to ICM entropy distribution, the process of virialization, and the role of AGN feedback in shaping large scale cluster properties.

Mining the CDA

My primary research makes use of a 350 observation sample (276 clusters; 11.6 Msec) taken from the *Chandra* archive. Of these 276 clusters, 16 lie in the redshift range $0.6 < z < 1.2$. Ongoing and future X-ray surveys will be heavily focused on the cluster population at $z > 1.0$. By gaining experience with low count, low surface brightness clusters now, I am amply prepared to work with much larger datasets of these objects in the future. In addition, this massive undertaking necessitated the creation of a robust reduction and analysis pipeline which 1) interacts with mission specific software, 2) utilizes analysis software (*e.g.* XSPEC, IDL), 3) incorporates calibration and software updates, and 4) is highly automated. Because my pipeline is written in a very general manner, adapting the pipeline for use with pre-packaged analysis tools from missions such as *XMM-Newton*, *Spitzer*, and *VLA* will be straightforward. Most importantly, my pipeline deemphasizes data reduction and accords me the freedom to move quickly into an analysis phase and generating publishable results.

Quantifying Cluster Virialization

The normalization, shape, and evolution of the cluster mass function are useful for measuring cosmological parameters. The evolution of large scale structure formation is a test of how dark matter and dark energy effect the cluster-scale evolution of dark matter halos, and therefore provides a complementary and distinct constraint on cosmological parameters to those tests which constrain them geometrically, such as supernovae and baryon acoustic oscillations.

However, clusters are a useful cosmological tool only if we can infer cluster masses from observable properties such as X-ray luminosity, X-ray temperature, lensing shear, optical luminosity, or galaxy velocity dispersion. Empirically, the correlation of mass to these observable properties is well-established. However, if we could identify a “2nd parameter" – possibly reflecting the degree of relaxation in the cluster – we could improve the utility of clusters as cosmological probes by parameterizing and reducing the scatter in mass-observable scaling relations.

One empirical method of quantifying the degree of relaxation involves using ICM substructure and employs the power in ratios of X-ray surface brightness moments. Although an excellent tool, power ratios suffer from being aspect-dependent. The work of Mathiesen & Evrard 2001 suggested a complementary measure of substructure which does not depend on projected perspective and could be combined with power ratio, axial ratio, and centroid variation to yield a more robust metric for quantifying a cluster’s degree of relaxation.

I have studied this auxiliary measure: the bandpass dependence in determining X-ray temperatures and what this dependence tells us about the virialization state of a cluster. The ultimate goal of this project was to find an aspect-independent measure for a cluster’s dynamic state. To this end, I have investigated the net temperature skew in my archive sample of the hard-band (2.0_{rest}-7.0 keV) and full-band (0.7-7.0 keV) temperature ratio for core-excised apertures. I have found this temperature ratio is statistically connected to mergers and the presence of cool cores. The next step is to make a comparison to the predicted distribution of temperature ratios and their relationship to putative cool lumps and/or non-thermal soft X-ray emission in cluster simulations. This will be carried out by a fellow graduate student as part of his thesis and funded by a successful *Chandra* theory proposal by Dr. Mark Voit which was motivated by my work. In addition, this project has produced a first author paper and has further stimulated the discussion for the continuing need of accurate cross-calibration between *XMM-Newton* and *Chandra*.

Cluster Feedback and ICM Entropy

The picture of the ICM entropy-feedback connection emerging from my research suggests cluster cD radio luminosity and core Hα emission are anti-correlated with cluster central entropy. Following analysis of 169 cluster radial entropy profiles (Fig. 1), I have found bimodality in the distribution of central entropy and central cooling times (Fig. 2) which is likely related to AGN feedback (and to a lesser extent, mergers). I have also found that clusters with central entropy $\lesssim 20$ keV cm^2 show signs of star formation (Fig. 3) and AGN activity (Fig. 4), while clusters above this threshold unilaterally do not have star formation and exhibit diminished AGN radio feedback. This entropy level is auspicious as it coincides with the Field length at which thermal conduction can stabilize a cluster core against ICM condensation. These results are highly suggestive that conduction in the cluster core is very important to solving the long-standing problem of how ICM gas properties are coupled to feedback mechanisms such that the system becomes self-regulating.

The final phase of my thesis is focused on further understanding why we observe bimodality, what role star formation is playing in the cluster feedback loop, refining a model for how conduction couples feedback to the ICM, and examining the peculiar class of objects which fall below the Field length criterion but *do not* have star formation and/or radio-loud AGN (blue boxes with red stars in two of the figures).

There are additional areas of my present research I'd like to expand on in the future. **(1)** To check if bimodality is archival bias, I am submitting a *Chandra* Cycle 10 observing proposal for a sample of clusters which predictably fall into the $t_{\rm cool}$ and K_0 gaps. **(2)** Two classes of peculiar objects warrant intensive multiwavelength study: high-K_0 clusters with radio-loud AGN (*e.g.* AWM4) and low-K_0 clusters without any feedback sources (*e.g.* Abell 2107). The former likely have prominent X-ray corona, while the latter may be showing evidence that extremely low entropy cores inhibit the growth of gas density contrasts. **(3)** Thus far I have only focused on AGN which are radio-loud according to the 1.4 GHz eye of NVSS, but recent work has shown AGN radio halos are very powerful at low frequencies too. I'd like to know what the radio power is at these wavelengths for (ideally) my entire thesis sample and see if the K_0-radio correlation tightens. **(4)** Using the near-UV sensitivity of *XMM*'s Optical Monitor and the far-IR channels of *Spitzer*, I plan to propose a joint archival project to disentangle which $K_0 \lesssim 20$ cDs are star formation dominated and which are AGN dominated.

Future Work with *Planck*

As I mentioned earlier, there are several extensions of my thesis work which I can pursue independently. But in the context of the post-doc position at Saclay and specifically working toward exploitation of the *Planck* cluster catalogue, I see a multitude of projects. Unless it is possible to commandeer *XMM-Newton* and *Chandra* for an entire year, X-ray follow-up of every SZ detected cluster is not possible. It is therefore of the utmost importance to calibrate SZ flux to mass scale so that a robust scaling relation can be used to directly infer masses from SZ observations. But while this sounds simple, there are complications which must be sorted out prior to the analysis of a large SZ cluster catalogue like *Planck*'s.

Existing studies so far suggest there is no redshift evolution in X-ray mass-scaling relations. But these studies suffer from a major flaw: they are hardly complete or unbiased. It would be wise to carefully select a representative sample of clusters, calculate their masses using a "robust, low-scatter" proxy (*e.g.* the Y_X parameter of Kravtsov et al. 2006), and check for redshift dependence in mass-scaling relations. There is the added complication that non-gravitational effects in clusters (*i.e.* AGN feedback, radiative cooling, and especially mergers) become more important at higher redshifts and at the lower end of the mass spectrum where the SZ effect will be a valuable probe. Understanding how these processes conspire to scatter a cluster away from tight scaling relations will also be integral to utilizing SZ flux for mass determination.

Beyond the technical issues and preparatory work, the *Planck* cluster catalogue will be a powerful observational tool. One can readily select interesting sub-samples (such as the 100 SZ brightest clusters) to be used in other studies, for example a study of their entropy distributions using *Chandra*data. From my own work and the work of people like Ian McCarthy and Michael Balogh, we know some clusters must have experienced some amount of "pre-heating" to reach the entropy levels seen in the ICM at present ($K > 150$ keV cm^2).

Because the normalization of the Y-M relation if sensitive to pre-heating, the SZ effect can be used to place constraints on the level of pre-heating which occurred at high-redshift, and thus can tell us about the feedback mechanisms which were active in clusters at early epochs – mechanisms which most likely played a role in shaping properties of the earliest galaxies. There are many other uses for the catalogue: combining SZ and Z-ray data to constrain H_0, analyzing the SZ power spectrum of clusters to constrain the dark energy equation of state, measuring f_{gas} for a sample of clusters and truly testing it's utility as a cosmology tool, the presence of high energy electrons (even at the low spatial resolution of *Planck*) would be confirmation that non-thermal processes are important in cluster formation (*e.g.* from AGN bubbles), and there is even the possibility that cooling flows could be identified by culling outliers from scaling relations.

Models of cluster formation, evolution, feedback, and dynamics are converging such that use of clusters in high precision cosmology is possible. I have the skill sets necessary to make meaningful and unique contributions both now and in the future of this field. Given the opportunity to branch out from my X-ray roots, I will be an excellent collaborator for maximizing the scientific returns of *Planck*'s galaxy cluster studies.

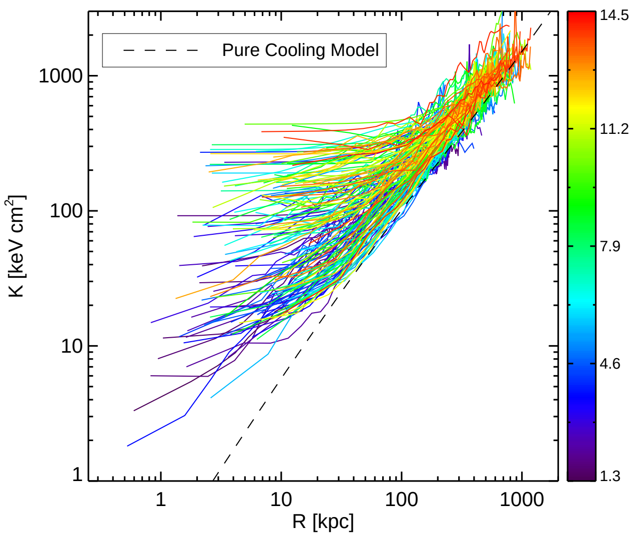

Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 70$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

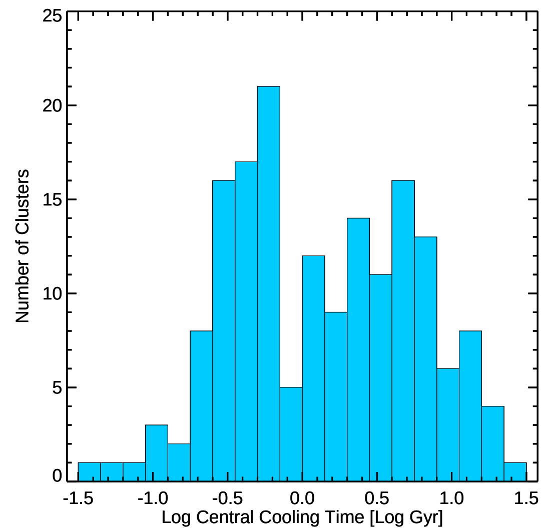

Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct gap at $0.6-1$ Gyr. An explanation for this bimodality does not currently exist.

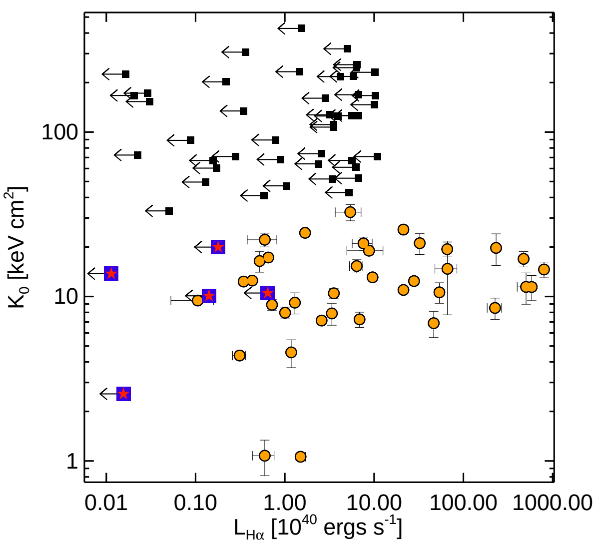

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction no longer balances radiative cooling and condensation of low entropy gas onto a cD can proceed.

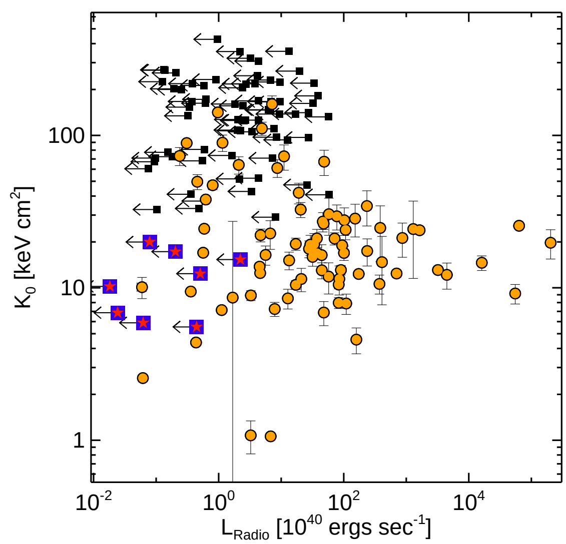

Figure 4: Central entropy plotted against NVSS radio luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Radio-loud AGN clearly prefer low entropy environs but the dispersion at low luminosity is large. It would be interesting to radio date these sources as this figure may have an age dimension.

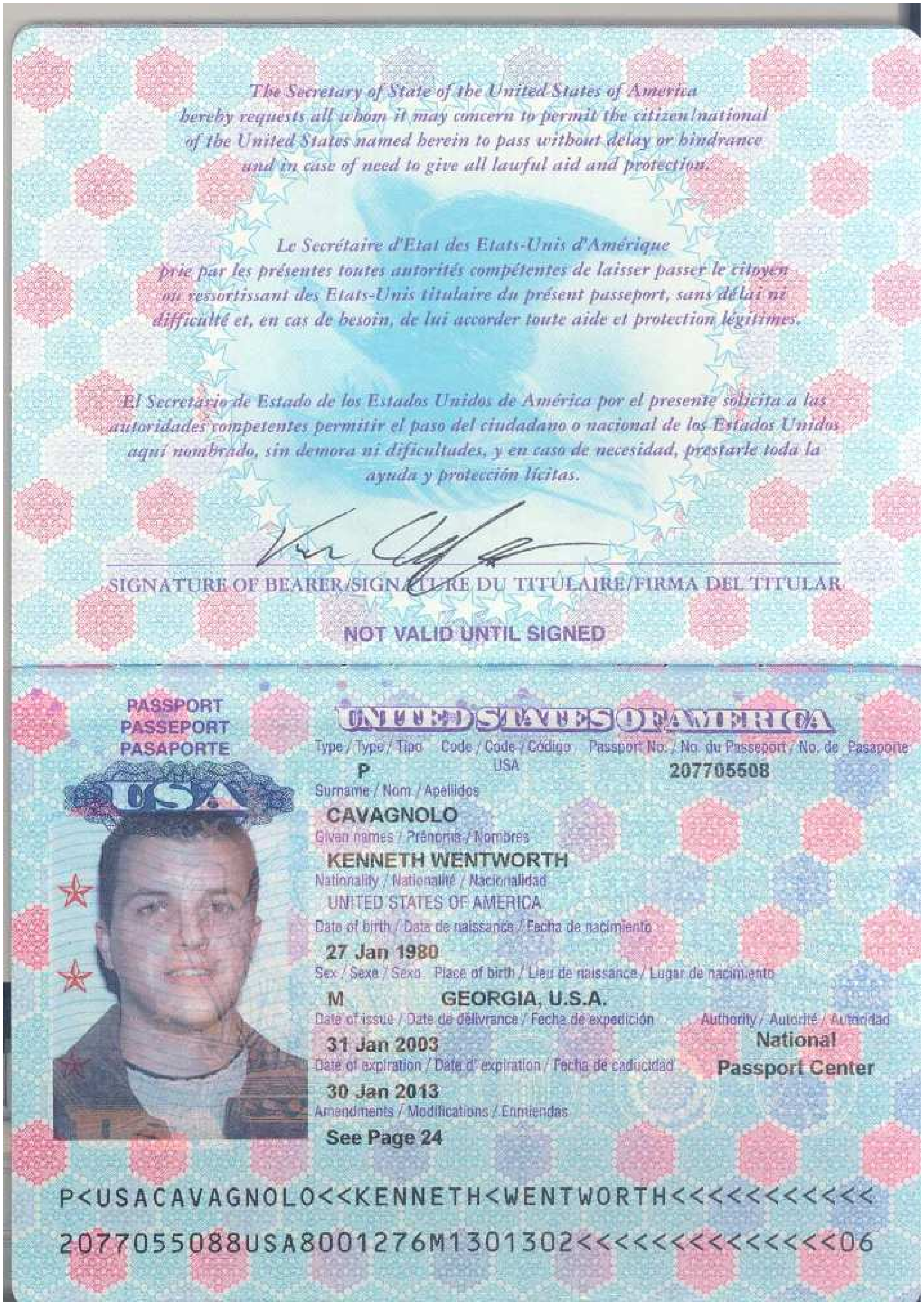

Figure 1: Passport for Kenneth W. Cavagnolo